BSR 4159

Laser Geodynamic Satellite Thermal/Optical/Vibrational Analyses and Testing

Final Report

Volume II
Technical Report

Book 1

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Contract NAS 8-30658

October 1974

Prepared for:

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Bendix Aerospace Systems Division

Ann Arbor, Michigan

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FOREWORD

This technical report presents the results of the LAGEOS Phase B Thermal/Optical/Vibrational Analyses and Test Program. The study was conducted by the Bendix Corporation, Aerospace Systems Division, for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, under Contract NAS 8-30658.

The results of this study are contained in two volumes, which are prepared and submitted in accordance with the data requirements of Contract NAS 8-30658, as follows:

Volume I	Executive Summary
Volume II	Technical Report

The study program was initiated in January 1974, the technical effort was completed in September 1974 and the final report was completed in October 1974. The effort was conducted under the direction of Mr. D. R. Bowden, LAGEOS Program Manager, and Mr. C. W. Johnson of the LAGEOS Program Office, NASA-MSFC, Code PD-LA-MGR.

The successful and timely completion of these analyses and test efforts is attributed to the conscientious and devoted efforts of J. Zurasky, R. Creel and C. W. Johnson of NASA-MSFC and E. Granholm, J. Maszatics, J. Monroe and L. Lewis of Bendix, under the direction of J. Brueger, Bendix Program Manager. The essential cooperation and assistance of P. Forman, C. Zanoni, S. Laufer and W. Fox at Zygo Corporation in Middlefield, Connecticut (retroreflector fabrication, Far-Field Diffraction Instrument development and test program support) and, of M. Kahan, M. Rimmer, D. Byrd and J. Mieron at the Optical Systems Division, Itek Corporation in Lexington, Massachusetts (retroreflector thermal/optical analyses) are also gratefully acknowledged.

VOLUME II

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1.0 INTRODUCTION

This report documents the results of the LAGEOS Thermal/Optical/Vibrational Analyses and Test Program (Contract NAS 8-30658), conducted for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, from January through September 1974. The purpose of this study is to verify, through analyses and tests, that the MSFC LAGEOS design inherently provides a retroreflector thermal environment which maintains acceptable retroreflector internal thermal gradients. Acceptable thermal gradients are those which result in less than 50% degradation of optical performance from isothermal optical performance.

This volume contains the technical results of the study, organized by the major task areas. The inter-relationships of the major tasks are also described and the major design decisions, during the program, are also identified. For narrative brevity and technical accuracy, detailed analyses and test results are provided in the original published format and as raw test-date in the as-run test procedure, respectively, as a series of appendices with this report.

Results of a retroreflector performance improvement effort, begun in September 1974, will be documented in an addendum to this report, to be issued upon the completion of that effort.

2.0 STUDY PROGRAM SUMMARY

The overall objectives of the LAGEOS Thermal/Optical Vibrational Analyses and Test Program, to meet the study purpose of LAGEOS design performance verification, are as follows:

- Develop a LAGEOS thermal model and conduct thermal analysis, using this model, to predict retroreflector thermal behavior.
- Procure and fabricate test hardware required to simulate the LAGEOS design for the purpose of conducting environmental tests.
- Accomplish thermal, optical, and mechanical vibration tests to verify that the thermal model and thermal analysis predictions are representative of actual satellite performance.

The study was conducted by the accomplishment of a number of major task areas, which were intended to provide the technical results to meet the study objectives. These tasks, defined in detail in the Program Study Plan (reference A), are as follows:

- Task 1 -- Develop Thermal Model and Perform Thermal Analyses. The LAGEOS thermal model was developed and parametric analyses results and final LAGEOS Satellite temperature predictions were generated; the results are discussed in Section 3.0.

  The Thermal/Optical Analysis, included in this task, was conducted by Itek and the Itek Final Report is included in this report.

- Task 2 - Provide the LAGEOS Test Article. Six (6) LAGEOS retroreflectors were procured from the Zygo Corporation. The LAGEOS test article was designed and fabricated to simulate the LAGEOS design, including the installation of the six LAGEOS retroreflectors. The test article was utilized in three configurations, as planned, in the thermal/optical and vibrational tests of Task 3. The design, including design criteria and rationale, are described in this report.

  This task also included the design, fabrication and assembly of a thermocouple fixture, installed in the test setup during thermal/optical tests and instrumented to provide temperature gradient measurements data. The design is described in this report.

- Task 3 - Conduct Thermal/Optical and Vibration Tests. A test plan was developed and, subsequently, test procedures were generated for each of the two major tests. The final versions are included in this report.

  The test arrangement for the thermal/optical tests was developed and the various test fixtures were identified, designed and fabricated. Test equipment, instrumentation and expendables were identified and provided to support the tests.

  The thermal/optical tests were run as planned and a number of additional test conditions were run. Data was recorded, reduced and evaluated.

  The vibration tests were run as planned and the results were recorded and evaluated.

  Test results are included in this report as raw data with the "as-run" test procedures and as reduced data. Conclusions and recommendations which result from the evaluation of the test results are also included.

A dynamic model was generated and a dynamic analysis was made of the initial baseline LAGEOS design, the hex-faced retroreflector design, to support the selection of the final LAGEOS design. Results, conclusions and recommendations are presented.

Analysis of the circular-faced retroreflector design, based on ALSEP test history, and of the LAGEOS acoustic environment were also made and results and conclusions are included in this report.

Overall program conclusions and recommendations are summarized in the final section of the report.

3.0 THERMAL MODEL AND THERMAL ANALYSIS

The objectives of this portion of the Phase B effort (Task 1.0 of reference A) are to perform a parametric thermal evaluation of various retroreflector mounting arrangements to minimize retroreflector thermal gradients, to generate a LAGEOS thermal model for the selected MSFC LAGEOS design, and, using this model, to predict thermal gradients for the LAGEOS retroreflectors in the prescribed satellite orbit. (Task 1.0 also includes the thermal/optical performance analysis which is discussed in Section 5.)

3.1 Parametric Thermal Analysis

The parametric thermal analysis was based on the identification of the hex-faced retroreflector (GEOS-C type) as the initial MSFC baseline design configuration and of the circular-faced retroreflector (ALSEP type) as the back-up design configuration. Results of this effort were presented in the First Program Review and are included in Appendix A, the Program Review Report. The results of this portion of the thermal analysis supported the selection of the final retroreflector design configuration at the First Program Review.

3.2 Selection of the LAGEOS Retroreflector Design

After review of the parametric thermal analysis results (together with the vibrational analysis results described in Section 4) at the Program Review, the circular-faced retroreflector design configuration was selected as the MSFC LAGEOS design. The bases for the selection are summarized in the Program Review Minutes, Appendix B. Subsequent thermal/optical analysis efforts, and ultimately the thermal optical tests, were thereafter based on the circular-faced configuration.

3.3 Post-Selection Parametric Analyses

After selection of the circular-faced retroreflector design, the parametric analyses cases were completed by the generation of temperature distribution predictions for a mount design with a 1-cm recess depth to the front face of the retroreflector. The results are summarized in Appendix C.

3.4 Thermal/Optical Analyses Input Data

Initially, it was planned to generate optical performance predictions for only one thermal gradient condition, the worst-case orbital condition. After selection of the circular-faced retroreflector design configuration, the thermal model was updated to incorporate the final mount design details.

Thermal gradient predictions were then generated for various orbital conditions and two satellite cavity temperatures, equivalent to two different satellite surface finishes. The single worst-case predictions were selected from these results, which are summarized in Appendices D and E.

An expansion of the optical analysis effort was directed by NASA-MSFC and it was then necessary to define two additional sets of thermal gradient predictions and two "unit gradient" predictions. These are summarized in Appendix F, as they were coordinated with MSFC and provided to Itek to perform the optical analyses, which is described in Section 5.

3.5 Test Condition Analysis

Additional gradient predictions, which are peculiar to potential test conditions, were also generated. The results are summarized in Appendix G and they confirm that the optical analysis input gradients include the maximum predicted temperature gradients.

A transient thermal analysis was conducted to predict test item stabilization times for changing chamber envivonmental conditions, maximum allowable optical viewing time before temperature gradient criteria are exceeded and test item temperature restabilization times. The results are summarized in Appendix H.

3.6 Final Satellite Thermal Analysis

After selection of the circular-faced retroreflector and definition of the LAGEOS retroreflector ring-mount design by MSFC, the design details were incorporated in the Bendix LAGEOS thermal math model. Thermal gradient predictions were generated prior to the thermal/optical tests for the bare machined-aluminum satellite design. The results are summarized in Appendix J.

After evaluation of the thermal data measured in the thermal/optical tests, the satellite thermal math model was correlated with the test results. Final satellite thermal gradient predictions were then generated and the results are summarized in Appendix K. The LAGEOS satellite thermal math model description is also included in Appendix K to meet a data submittal requirement of the Study Plan (reference A).

3.7 Thermal Analysis Summary

The thermal analysis task results were summarized in the final presentation at the MSFC LAGEOS PDR. This summary is included in Appendix L.

3.8 Conclusions and Recommendations - Thermal Analysis

The conclusions and recommendations of this thermal analysis effort are summarized in pages L-27 through L-29 of Appendix L.

4.0 DYNAMIC MODEL AND VIBRATIONAL ANALYSIS

The objective of this Phase B effort (Task 3.6 of reference A) is to conduct a dynamic analysis of the baseline LAGEOS retroreflector mount design and, based on the results, provide inputs to support the selection of the final mount design geometry.

4.1 Dynamic Analysis of Initial Baseline Design

The evaluation of the hex-faced retroreflector and the GEOS-C type clip mount design, the initial LAGEOS baseline design, was completed for the First Program Review, except for the maximum stress predictions for the clip design during exposure to the sinusoidal vibration environment. The dynamic model description and the analysis results are summarized in Appendix A. It should be noted that the results and the conclusions shown are as updated (1 June 1974) to reflect the maximum stress predictions completed after the review. The updated results add an additional reason (i.e., the unacceptable stress level) for the requirement to redesign the clip mount, if the hex-faced retroreflector had been retained as the LAGEOS design. Since the Program Review conclusions resulted in the adoption of the circular-faced retroreflector as the LAGEOS design, the results are now only of academic interest.

The early dynamic testing of the mount design, originally in the program, was deleted as part of a program change to increase the thermal/optical testing, since dynamic testing was also planned for the final test article.

4.2 Conclusions and Recommendations - Dynamic Analysis

Subsequent to the Program Review, an evaluation of the LAGEOS acoustic environment was made with respect to the need for acoustic testing of the test article. The results are summarized in Appendix M and are the basis for no acoustic tests, since the vibration tests already expose the test article to a more severe environment.

Also, as a result of an action item identified at the First Program Review, an evaluation of ALSEP analysis/test data was made to provide rationale for confidence in the structural integrity of the circular-faced retroreflector and its ring mount in the LAGEOS application. Results of this evaluation are summarized in Appendix N. It was concluded that the LAGEOS dynamic environment would not subject the circular-faced retroreflector to excessive stress levels. Subsequently, the vibration tests of the LAGEOS test article (discussed in Section 7) successfully demonstrated the LAGEOS design integrity.

5.0 THERMAL/OPTICAL ANALYSIS

The objective of this effort is to predict LAGEOS retroreflector optical performance for the expected worst-case thermal gradients resulting from the LAGEOS orbit.

5.1 Thermal/Optical Analysis Requirements

Initially, optical performance was to be generated for the nominal LAGEOS retroreflector configuration under both the isothermal condition andthe set of thermal gradients, representative of the single worst-case orbit thermal condition. A program change increased the number of isothermal cases to include both a nominal (or "perfect") retroreflector configuration and a "tolerance" retroreflector configuration, having dihedral angles covering the full specified tolerance range. The program change also increased the number of thermal gradient cases to three (3), to cover a range of temperature gradients for the nominal retroreflector, and added one (1) thermal gradient case for the "tolerance" retroreflector. In addition, two "unit gradient" cases ("unit axial gradient" and "unit radial gradient") were added to permit the evaluation of these separate effects. The optical analysis cases are summarized in Appendix P; the input thermal gradients for each case are those defined in Appendix F.

5.2 Thermal/Optical Analysis Results

The expertise and proprietary optical design computer programs of the Itek Corporation were utilized to perform the thermal/optical analyses. The Itek experience in retroreflector optical analysis includes the generation of predicted thermal/optical performance of the ALSEP LRRR retroreflectors for Bendix on the Apollo Program.

The inputs, the thermal/optical math model description, and the analyses results are described, in detail, in Appendix Q. The optical analyses results are also summarized in the final presentation handout, Appendix L (pages L-33 through L-52).

5.3 Conclusions and Recommendations - Thermal/Optical Analysis

The conclusions and recommendations of the thermal/optical analysis effort are summarized on pages L-49 and L-50 of Appendix L.

Other conclusions and recommendations, which relate the the comparison of predicted optical performance with optical test performance measurements, are included in Section 5.

6.0 THERMAL/OPTICAL TESTS

The objectives of this portion of the Phase B Program are to experimentally determine the thermal/optical performance of the MSFC LAGEOS design under isothermal and orbital worst-case thermal conditions and to experimentally identify any effects of the launch/boost vibration environment on the thermal design and optical performance. A directly related portion of the Phase B Program is the task to provide the LAGEOS test article, which is also described in this section.

6.1 Test Plan

The LAGEOS Phase B Test Plan was generated to describe the overall plan for accomplishing the various tests required to achieve the study program objectives. The plan identifies the requirements for each test for program review purposes, for the design and fabrication of the LAGEOS test article and test fixtures, for the allocation planning of test facilities, equipment and expendables and for the generation of detail test procedures by which the required test data will be obtained.

The initial issue of the Test Plan was released on 15 April 1974 and the plan was updated twice to incorporate review comments and directed program changes. The final issue, dated 12 July 1974, is included as Appendix R. This plan reflects the test program prior to the start of the actual tests. The program was expanded and modified during the testing and the final test conditions are as described in the "as-run" test procedure, Appendix S.

6.2 Test Article

The LAGEOS test article is a hardware assembly, including six (6) LAGEOS retroreflectors, the design of which directly represents specific critical LAGEOS design parameters to ensure credible thermal/optical performances. The test article design criteria and the LAGEOS design parameters represented in the test article are summarized as Appendix L. The design requirements are discussed in even greater detail in Appendix R.

Drawings of the test article hardware, as fabricated, are shown in Appendices L and R. The mounting ring designs were based directly on the MSFC LAGEOS design but were modified as outlined in the Final Presentation (page L-68 of Appendix L) to maintain a .002 to .006 inch clearance between the retroreflector tabs and the upper mounting ring. This clearance requirement is based on ALSEP experience and is a compromise between structural integrity requirements and minimum thermal conductivity and thermal expansion/contraction loads on the retroreflector.

The retroreflectors installed in the test article were fabricated by the Zygo Corporation of Middlefield, Connecticut. Retroreflector design and characteristics are summarized in the Final Presentation (pages L-72 and L-85 respectively, of Appendix L). Data sheets for each test retroreflector are included in Appendix T.

6.3 Test Methods

The test arrangement for the thermal/optical tests is shown in the layout drawing and the photographs included in the Final Presentation (pages L-59 through L-63 of Appendix L). The test arrangement requirements necessitated the design and fabrication of a number of test fixtures, as follows:

- Thermal Optical Test Fixture
- Optical Window and Shield Assembly
- Far-Field Diffraction Instrument Support Plate
- Thermocouple Fixture

The requirements, functions and design of each of these fixtures is described, in detail, in Appendix R.

The locations of the thermocouple instrumentation, on both the thermocouple fixture and the test article, are identified in the "as-run" test procedure, Appendix S.

The basic optical performance measurement instrumentation is provided by the Zygo Far-Field Diffraction Instrument (FFDI). This instrument, developed with Bendix capital equipment funding, was designed and fabricated by the Zygo Corporation. The instrument overall design characteristics and an optical schematic of the design are shown in Appendix L. In addition, the FFDI measurement outputs are summarized and the FFDI scale factor determination is described in Appendix L. A photograph of the FFDI in the test arrangement is also shown in Appendix L.

The final set of test conditions planned to be used in the thermal/optical tests is shown in the Test Plan, Appendix R. The test conditions were expanded during actual testing and the final set of test conditions is shown in the "as-run" test procedure, Appendix S. The final set of test conditions are also summarized in Appendix L, in a format which can be used as a guide, or index, for finding data for a specific set of test conditions.

6.4 Test Results - Thermal Optical Tests

The test results, in the form of raw recorded test data, are given in the "as-run" test procedure, Appendix S. The FFDI photographic output data are shown in Appendix U.

The raw data was selectively reduced to show the significant results. The test data reduction techniques are summarized in Appendix L. Isothermal/ambient performance is tabulated and isothermal/vacuum data is plotted for each retroreflector as a function of laser field (incident) angle and is shown in Appendix L.

In addition, the no sun - no earth IR thermal cases are plotted, for each retroreflector, to show optical performance as a function of laser field angle. The ratio of relative performance at the thermal condition to the relative performance at the isothermal condition is also plotted as a function of cavity core temperature (i.e., thermal condition). Review of this data, shown in Appendix L, indicates that the maximum degradation due to thermal gradients is about 35% (i.e., less than the 50% maximum permitted. Reduced data for the 1 sun - no earth IR and the no sun - 1 earth IR cases are also shown in Appendix L and indicate even less degradation due to the resulting thermal gradients.

In all of the reduced data, the relatively large differences in optical performance between individual retroreflectors is noted.

The optical performance for the Serial No. 3 (Cavity "A") retroreflector is compared with the optical analysis results for the "tolerance" retroreflector design in Appendix L. Although the dihedral angles compare favorably, the optical performance data differs significantly. This difference is attributed to the difference in the measured location of the far-field diffraction pattern high-intensity ring (from far-field pattern photographs) versus the location of the annulus mask used to measure the return beam relation intensity, as shown in Appendix L.

Performance differences at thermal/vacuum conditions may be attributed to differences in the thermal gradients between the analytical case and the test case (difficulties were experienced in directly measuring thermal gradients on the retroreflectors). It was shown in the optical analysis (Section 5) that axial gradients can compensate for degradation due to radial gradients and manufactured wavefront deviation.

Optical performance results obtained before and after the vibration tests are also reduced and shown in Appendix L. The comparison data is for two of the retroreflectors which remained in the same orientation throughout the pre-vibration and post-vibration optical tests. Only minor changes can be noted in the pre-vibration and post-vibration data.

6.5 Conclusions and Recommendations - Thermal/Optical Tests

The conclusions reached on the basis of the thermal/optical tests are described in the Final Presentation, Appendix L, and these can be summarized as follows:

- The LAGEOS design demonstrates acceptable performance degradation under worst-case orbital thermal conditions.
- No significant thermal/optical performance changes result from exposure to the LAGEOS launch/boost vibration environment.
- The present retroreflector dihedral angle tolerance of ± 0.5 arc sec results in relatively large optical performance differences between retroreflectors.

In addition, the following major conclusion resulted from evaluation of the test results at the PDR:

- The nominal dihedral angle specified for the LAGEOS retroreflectors appears to be too large for optimum return intensity in the annular region of interest (13.2 to 16.9 arc-sec diameters) in the far-field diffraction pattern. The measured dihedral angles for the test retroreflectors are based on direct mechanical measurement, using an autocolimator and a precision index table.

The recommendations made at the Final Presentation are described in Appendix L and are summarized as follows:

- Modify MSFC mounting hardware drawings to reflect the test article mounting hardware design.
- Consider a retroreflector dihedral angle tolerance change if LAGEOS system evaluation indicates more uniform retroreflector performance is required.
- Consider additional thermal/optical analyses and tests to support additional retroreflector performance data requirements for LAGEOS system analysis.

A final recommendation, relating to the major conclusion reached at the PDR, is as follows:

- Reverify the measured dihedral angles for each test retroreflector, analytically determine the "effective" dihedral angles from Twyman-Green interferograms for each retroreflector and rework the test retroreflector dihedral angles and confirm performance improvements by optical tests.

7.0 VIBRATION TESTS

The objective of this portion of the Phase B effort is to subject the LAGEOS test article to the worst-case sinusoidal and random vibration environments, representative of the LAGEOS satellite qualification-level launch/boost environment. The test is intended to demonstrate the structural integrity of the LAGEOS retroreflector/mount design and to determine the effect, if any, on thermal/optical performance of the design.

7.1 Test Set-Up

The test set-up involves the installation of the LAGEOS six-retroreflector test article on a vibration fixture which, in turn provides the tie-down interface with the Bendix vibration test system shaker head or slip-plate. The vibration fixture is instrumented with a control accelerometer,oriented in the axis being tested. The set-up is described in detail in the Vibration test procedure, Appendix V, and is shown in photographs in Appendix L.

7.2 Test Results

The actual test sequence and real-time test results are described in the "as-run" test procedure, Appendix V. Although one apparent anomaly (test discrepancy) was reported, later investigation confirmed that the retroreflector condition noted had existed prior to the test. The details of the anomaly investigation results are described in Appendix L. The vibration test, therefore, demonstrated the structural integrity of the LAGEOS design.

The results of the thermal/optical testing, before and after the vibration exposure, are discussed in Section 6.

7.3 Conclusions and Recommendations - Vibration Tests

The conclusions, with respect to the vibration tests, are summarized in Appendix L and, with respect to vibration exposure on optical performance, in Section 6.

As summarized in Appendix L, the LAGEOS acoustic environment is shown to be negligible, compared to the vibration environment, and it is, therefore, concluded that LAGEOS integrity will not be affected by the acoustics environment.

8.0 FINAL PRESENTATION

The Phase B Study Plan (reference A) requires the reporting of the overall results of the study program in a final presentation at MSFC.

At MSFC request, this presentation was made as part of the LAGEOS Program PDR at MSFC on 3-4 September 1974. Bendix, Itek and Zygo representatives participated in the Bendix Phase B Program Final Presentation. The summary of results for the analyses and test portions of the Phase B program, and the conclusions and recommendations presented, served to support the overall PDR conclusion that the MSFC LAGEOS design had been confirmed as ready to proceed into the Phase C/D program.

The Final Presentation handouts summarize all of the data presented, plus additional data included for clarification of specific areas, and are included as Appendix L.

Review Item Discrepancies (RID), generated during the PDR, including those related to the Bendix program final presentation, and the results of the RID review and disposition by the PDR board are described in reference B. None of the RIDs directly impact the Phase B results and are therefore mentioned only as reference information.

9.0 CONCLUSIONS AND RECOMMENDATIONS SUMMARY

9.1 Conclusions

The major conclusions of this study, based upon the results developed in the major task areas and documented in this report, are summarized as follows:

- The LAGEOS design demonstrates acceptable performance (less than 50% degradation) under worst-case orbital thermal conditions.

- No significant thermal/optical performance degradation results from exposure of the LAGEOS design to the LAGEOS launch/boost vibration environment.

- The nominal dihedral angle (90° 0' 1.5"), as specified for LAGEOS retroreflectors, appears to be too large for optimum return intensity within the LAGEOS far-field diffraction pattern annular region (13.2 - 16.9 arc-sec diameters).

- The present dihedral angle tolerance ($\pm$0.5") results in relatively large optical performance differences between individual retroreflectors.

- The LAGEOS launch/boost acoustic environment is negligible, compared to the vibration environment; therefore, it is concluded that no effect on LAGEOS thermal/optical performance will result from exposure to the acoustic environment.

- The close agreement, between thermal predictions and thermal test results (within 5°C), provides confidence that satellite thermal gradients are accurately predicted by the LAGEOS thermal model.

- Based on thermal/optical analyses results, it is concluded that optical performance is relatively insensitive to irregular dihedral angle tolerances (i.e., angles distributed on each side of nominal) and manufactured surface quality effects; optical performance varies considerably when dihedral angles change in the same direction from the 1.5 arc sec nominal (i.e., relative performance changes from 21.6% to 14.9% for a +0.6 arc sec dihedral angle change).

- Thermal/optical performance varies only about 1% in relative performance for the range of thermal gradients evaluated in the thermal/optical analyses.

- Thermal/optical performance is sensitive to individual unit thermal gradients (i.e., only axial gradients or only radial gradients), but axial gradients compensate for radial gradients and for manufactured surface quality effects.

- The LAGEOS thermal model, based on the LAGEOS orbital characteristics and final design parameters and updated by the results of the thermal/optical tests, will provide detail satellite temperature distributions. A description of the final satellite thermal model, including nodal, resistive and heating information, in both tabulated data format and as a computer deck, have been provided to MSFC.

9.2 Recommendations

- The retroreflector cavity design should possess a low (less than 5%) infrared emittance to enhance radiative isolation.

- Thermal coatings/finishes which are applied to the satellite exterior surface should be of low solar absorption (i.e., high visible reflectance) to permit tracking by ground stations.

- Retroreflector mounting rings should have low thermal conductivity and should provide minimal contact with the retroreflector tabs for thermal design reasons. Loading of these tabs by the mounting rings should be avoided, including loads due to thermal expansion/contraction differences, to avoid retroreflector distortion. It is, therefore, recommended that the NASA-MSFC mounting hardware drawings be modified to reflect the LAGEOS test article mounting hardware design.

- Consider retroreflector dihedral angle tolerance specification reduction for more uniform performance (retroreflector-to-retroreflector) and for some performance improvement (if the nominal angle is optimized).

- Reverify the measured dihedral angles for each retroreflector and analytically determine the "effective" dihedral angles from Twyman-Green interferograms; confirm the performance improvement in optical tests of the test retroreflectors, after rework to the optimum dihedral angles.

- Consider additional thermal/optical analysis and test to more fully explore the effects of various design parameters in support of additional retroreflector performance data input requirements for the SAO LAGEOS system application analysis.

- Correlate the Itek thermal/optical math model with the actual retroreflector characteristics, the measured thermal/optical test conditions and with the SAO optical analysis model; generate new thermal/optical performance predictions to support the selection of the optimum dihedral angles.

10.0 REFERENCES

The following documents are referenced in this report:

A. Study Plan - Laser Geodynamic Satellite Thermal/Optical/Vibrational Analyses and Testing, Bendix Document LAGEOS-8, Revision B, dated 28 June 1974.

B. NASA-MSFC LAGEOS Preliminary Design Review Board Meeting Report, dated September 5, 1974.

Bendix

Aerospace
Systems Division

LAGEOS-17

APPENDIX A

Title:	First Program Review - LAGEOS Thermal/Optical/ Vibrational Analyses and Testing Program
Author:	Not Applicable
Type of Report:	DR No. MA-03 DPD No. 296
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Approved: John M. Bunger
LAGEOS Program Manager

INTRODUCTION

This LAGEOS Program Review is intended to fulfill the contract requirement for the first interim performance review of the Bendix LAGEOS Phase B program. The agenda has been coordinated with the MSFC LAGEOS Program Office and covers the results and/or status of the current program tasks, as defined in the Bendix Program Study Plan, LAGEOS-8, 15 March 1974.

LAGEOS PROGRAM REVIEW

APRIL 17-18, 1974

BENDIX AEROSPACE SYSTEMS DIVISION
ANN ARBOR, MICHIGAN

AGENDA

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BENDIX RESULTS/RECOMMENDATIONS	E. GRANHOLM, BXA
• DYNAMIC ANALYSIS/TEST	
MSFC STATUS	J. McBRIDE, MSFC
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• OPTICAL TESTS - MSFC STATUS	J. ZURASKY, MSFC
• SELECTION OF LAGEOS RETROREFLECTOR CONFIGURATION	MSFC/BXA
• FACILITIES TOUR	J. MONROE, BXA J. BRUEGER, BXA MSFC
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THERMAL/OPTICAL TEST FIXTURE OPTICAL WINDOW AND SHIELD ASSY FFDI PLATFORM ASSY VIBRATION TEST FIXTURE TEST EQUIPMENT AND EXPENDABLES	

AGENDA (CONTINUED)

TEST CONDITIONS	J. BRUEGER, BXA
· PROGRAM SCHEDULES/STATUS	J. BRUEGER, BXA
· STUDY PLAN REVIEW	MSFC/BENDIX

INTRODUCTION (CONTINUED)

The overall Bendix Phase B program is summarized in the LAGEOS Study Logic Network. This program review will present the results obtained in the performance of Subtasks 1.1, 1.2 and 3.6. There will be an opportunity in the review for MSFC representatives to present the results and status of their LAGEOS thermal, dynamics and optical efforts which complement the Bendix efforts. A major objective of this review is to then review the results to date and select the LAGEOS retroreflector configuration which is to be the basis of the analysis and test efforts for the remainder of the program.

The review will also present the status of Test Article and Test Program efforts, as performed in Subtasks 2.1, 2.2 and 2.3 and in Subtasks 3.1, 3.2 and 3.3, respectively. The efforts presently underway are preparatory to performance of the various tests in the remaining Subtasks. Test article configurations and test fixture designs will also be presented.

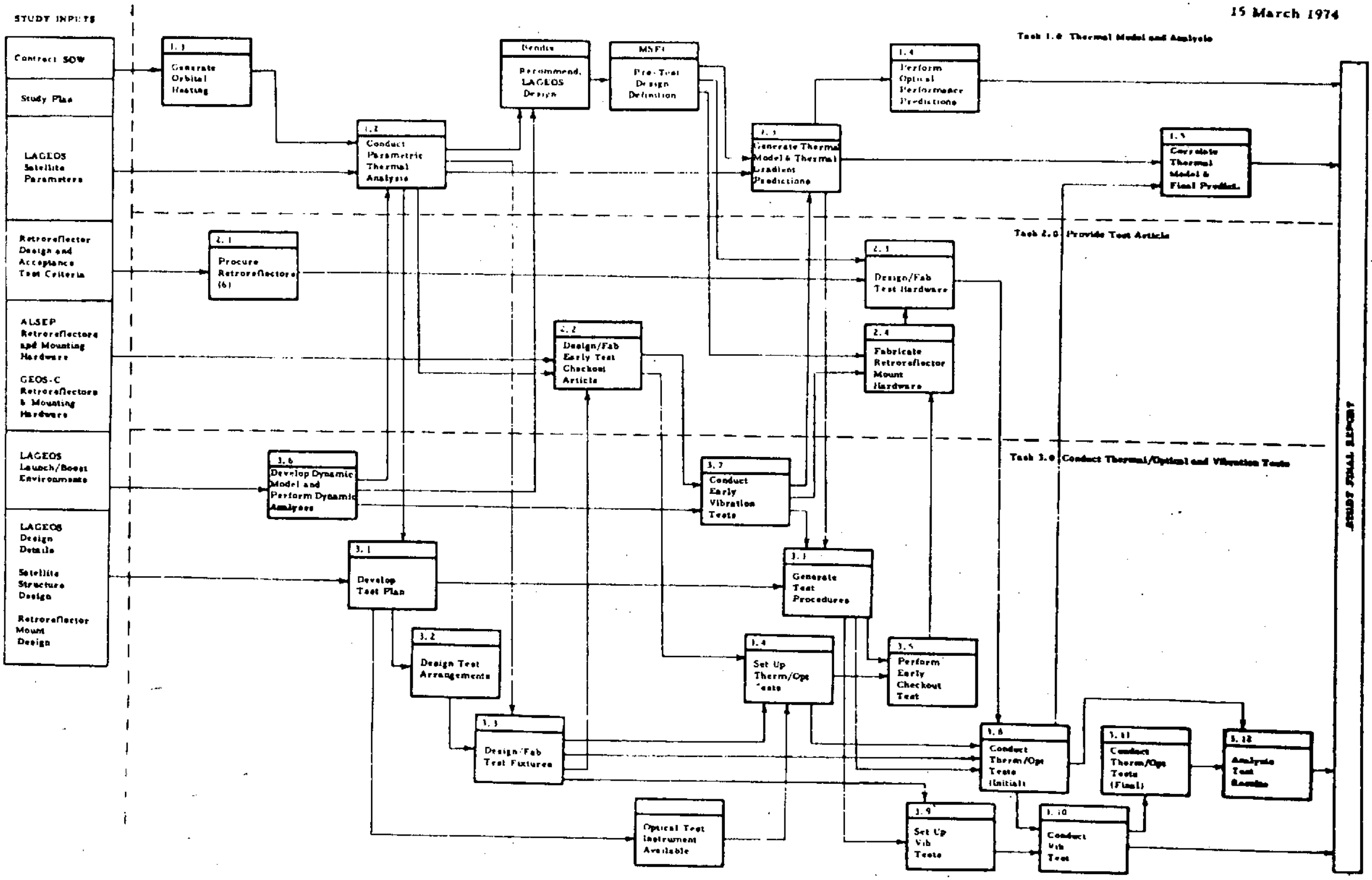

Figure 3-1 LAGEOS Study Logic Network

Bendix Aerospace Systems Division

LAGEOS

THERMAL/OPTICAL DESIGN AND ANALYSIS

E. Granholm
17 April 1974

THERMAL/OPTICAL DESIGN OBJECTIVES

The LAGEOS thermal/optical performance will be optimized if the individual retroreflectors can be maintained in a nearly isothermal state. The LAGEOS thermal design/analysis effort concentrates on minimizing axial and radial temperature gradients within the retroreflectors. To achieve this objective, the thermal design:

1. Thermally isolates the retroreflectors from the satellite structure (both radiation and conduction), and

2. Utilizes thermal control coatings and/or finishes which minimize retroreflector-to-satellite structure temperature differences.

LAGEOS
THERMAL/OPTICAL DESIGN OBJECTIVES

- MINIMIZE RETROREFLECTOR AXIAL AND RADIAL TEMPERATURE GRADIENTS BY LIMITING RETROREFLECTOR/SATELLITE STRUCTURE HEAT EXCHANGE.
- PROVIDE HIGH THERMAL RESISTANCE MOUNTING OF RETROREFLECTORS TO SATELLITE STRUCTURE.
- UTILIZE TEMPERATURE CONTROL TECHNIQUES WHICH MINIMIZE RETROREFLECTOR/SATELLITE STRUCTURE TEMPERATURE DIFFERENCES.

ORBITAL ENVIRONMENT PARAMETERS

The orbital parameters utilized in the LAGEOS thermal design/analysis constitute the worst-case hot environment. By allowing the satellite core temperature to arrive at its maximum level, corner temperature gradients will be upper-bounded and the corner optical performance will be lower-bounded. The maximum heating constants used to generate satellite incident direct-solar, albedo, and IR heating rates are those specified in MSFC documents TMX-64627 and S&E-ASTN-PF 72-67. Incident heating rates will not change appreciably if the orbit altitude of 5900 km is varied by ± 10%.

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ORBITAL ENVIRONMENT PARAMETERS

- ORBIT CHARACTERISTICS

  ORBITAL ALTITUDE = 5900 KM
  EQUATORIAL INCLINATION = 110°
  ORBITAL ECCENTRICITY $\leq$ 0.01
  SATELLITE ATTITUDE = NO PREFERRED ORIENTATION
  SATELLITE SPIN RATE = NO SPIN

- HEATING CONSTANTS FOR HOT (WORST CASE) ENVIRONMENT (DEFINED BY MSFC TMX-64627 AND S&E-ASTN-PF 72-67)

  SOLAR CONSTANT = 1412.5 W/M^2
  ALBEDO REFLECTANCE = 30%
  EARTH IR EMISSION = 237.0 W/M^2

- MAXIMUM INCIDENT HEATING RATES

  DIRECT SOLAR = 1412.5 W/M^2 (448.0 $BTU/HRFT^2$)
  ALBEDO = 38.1 W/M^2 (12.1 $BTU/HRFT^2$)
  EARTH IR = 66.5 W/M^2 (21.1 $BTU/HRFT^2$)

RETROREFLECTOR THERMAL PROPERTIES

The pertinent thermal/physical properties of T-19 Suprasil 1 are presented to provide a basis for comparing the MSFC and BxA thermal math models. Thermal conductivity, specific heat, and specific gravity were obtained directly from Amersil, Inc., Hillside, New Jersey. Values of IR emittance and volumetric solar absorptance create maximum temperature gradients in the retroreflector.

LAGEOS
RETROREFLECTOR THERMAL PROPERTIES

THERMAL PROPERTIES OF T-19 SUPRASIL 1 RECEIVED FROM AMERSIL, INC., HILLSIDE, NEW JERSEY.

- THERMAL CONDUCTIVITY

TEMP (°C)	K (CAL/SECCM°C)
-50	0.0030
20	0.0033
100	0.0035

- SPECIFIC HEAT

TEMP (°C)	Cp (CAL/GM°C)
-100	0.12
-50	0.14
0	0.17
100	0.23

- SPECIFIC GRAVITY = 2.20
- IR EMITTANCE = 90%
- VOLUMETRIC SOLAR ABSORPTANCE = 5%

TENTATIVE THERMAL CONTROL COATINGS

During the initial LAGEOS parametric thermal analysis, temperature control concepts which represent the range of passive heat transfer techniques were investigated. For a reflective coating, IIT's Z-93 was assumed to be applied to the satellite exterior surfaces. Z-93 coating has a successful history of performance for providing thermal control of the ALSEP LRRR's. Vacuum-deposited aluminum (VDA), which is also a space-qualified thermal coating,was selected to represent the absorptive design approach.

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TENTATIVE THERMAL CONTROL COATINGS

- COATINGS SELECTED TO BRACKET THE RANGE OF SOLAR ABSORPTANCE/IR EMITTANCE ($\alpha s/\epsilon ir$) RATIO FOR CONVENTIONAL TEMPERATURE CONTROL SURFACES.
- IIT'S Z-93 WHITE ZINC OXIDE COATING (REFLECTIVE)
  - αs = 0.16 - 0.22
  - ϵir = 0.89
  - $\Delta\alpha s$ 1 YEAR ULTRAVIOLET = 0.11
  - $\Delta\alpha s$ 1 YEAR SYNCHRONOUS ORBIT = 0.17
  - $\alpha s/\epsilon ir$ USED IN LAGEOS THERMAL ANALYSIS = 0.2/0.9
  - FLOWN ON ALSEP LASER RANGING RETROREFLECTOR ARRAYS
- VDA-VACUUM DEPOSITED ALUMINUM (ABSORPTIVE)
  - αs = 0.10 - 0.20
  - ϵir = 0.05
  - $\alpha s/\epsilon ir$ USED IN LAGEOS THERMAL ANALYSIS = 0.15/0.05

DESCRIPTION OF THERMAL MATH-MODEL

The thermal math-model generated to predict temperature levels and heat exchange rates for LAGEOS is described. Typical retroreflectors, installed at various locations on the satellite surface, are analyzed in detail. The structural elements and retroreflectors to be examined were selected to indicate potential thermal design problem areas.

DESCRIPTION OF THERMAL MATH MODEL

Item	Node Identification	Number of Nodes
Inertial Weight (30M20452)	1, 2	2
Half Sphere (30M20453)	3-12	10
Individual Retroreflectors (50M24466 50M24461)	25 - 42 Retro #1, Full Sun 50 - 67 Retro #2, 16° Off-Sun 75 - 92 Retro #3, 45° Off-Sun 100 -117 Retro #4, 180° Off-Sun 125 -142 Retro #5, 90° Off-Sun	18 Per Retro 90 Total
Clip (50M24467)	43 - 45 Retro #1 68 - 70 Retro #2 93 - 95 Retro #3 118 -120 Retro #4 143 -145 Retro #5	3 Per Clip 15 Total
Combined Retroreflectors	151 - 160	10
SPACE	201 - 206	6
TOTAL NODES	---------	133

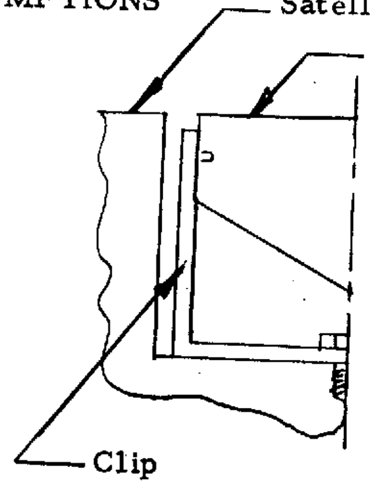
TOTAL NUMBER OF RADIATION AND CONDUCTION RESISTORS = 401

HEXAGONAL CORNER THERMAL DESIGN/ANALYSIS ASSUMPTIONS

The hexagonally-faced retroreflector and its associated mounting configuration was initially analyzed. The corner is suspended in its cavity at three points by a beryllium-copper clip. The clip prongs are considered to be bent inward 0.010 inches, before the corner is installed. This assumption is believed to create the worst-case (maximum) contact pressure on the corner, thereby maximizing conductive heat transfer between the cavity and the retroreflector. For this configuration, two thermal control coatings were investigated (Z-93 and VDA) and were assumed to be applied to the satellite exterior surface only. The cavity IR emittance corresponded to bare machined aluminum (cleaned and degreased) for both cases. Also, the face of the retroreflector was assumed flush with the satellite exterior surface.

LAGEOS

HEXAGONAL CORNER THERMAL DESIGN/ANALYSIS ASSUMPTIONS



- CORNER CUBE, HEXAGONAL (DWG NO. 50M24466).
- CLIP (DWG NO. 50M24467)

  PRONGS OF CLIP INITIALLY BENT INWARD 0.010 INCHES (WORST CASE CONTACT PRESSURE).

- SATELLITE STRUCTURE, HALF SPHERE CONCEPT (DWG NO. 30M20453)

  EXTERIOR SURFACES COATED WITH:

  7-10 MILS Z-93 (α_s/ϵ_{ir} = 0.2/0.9).

  1200-1500Å VDA (α_s/ϵ_{ir} = 0.15/0.05).

  INTERIOR SURFACES:

  BARE MACHINED ALUMINUM, CLEANED AND DEGREASED (ϵ_{ir} = 0.05).

SATELLITE STRUCTURE STABILIZATION TEMPERATURES - HEX CORNER

Satellite core temperatures for the hex-faced corner, mounted flush with the satellite surface and with Z-93 coating applied on the satellite,are presented. The highlights are as follows:

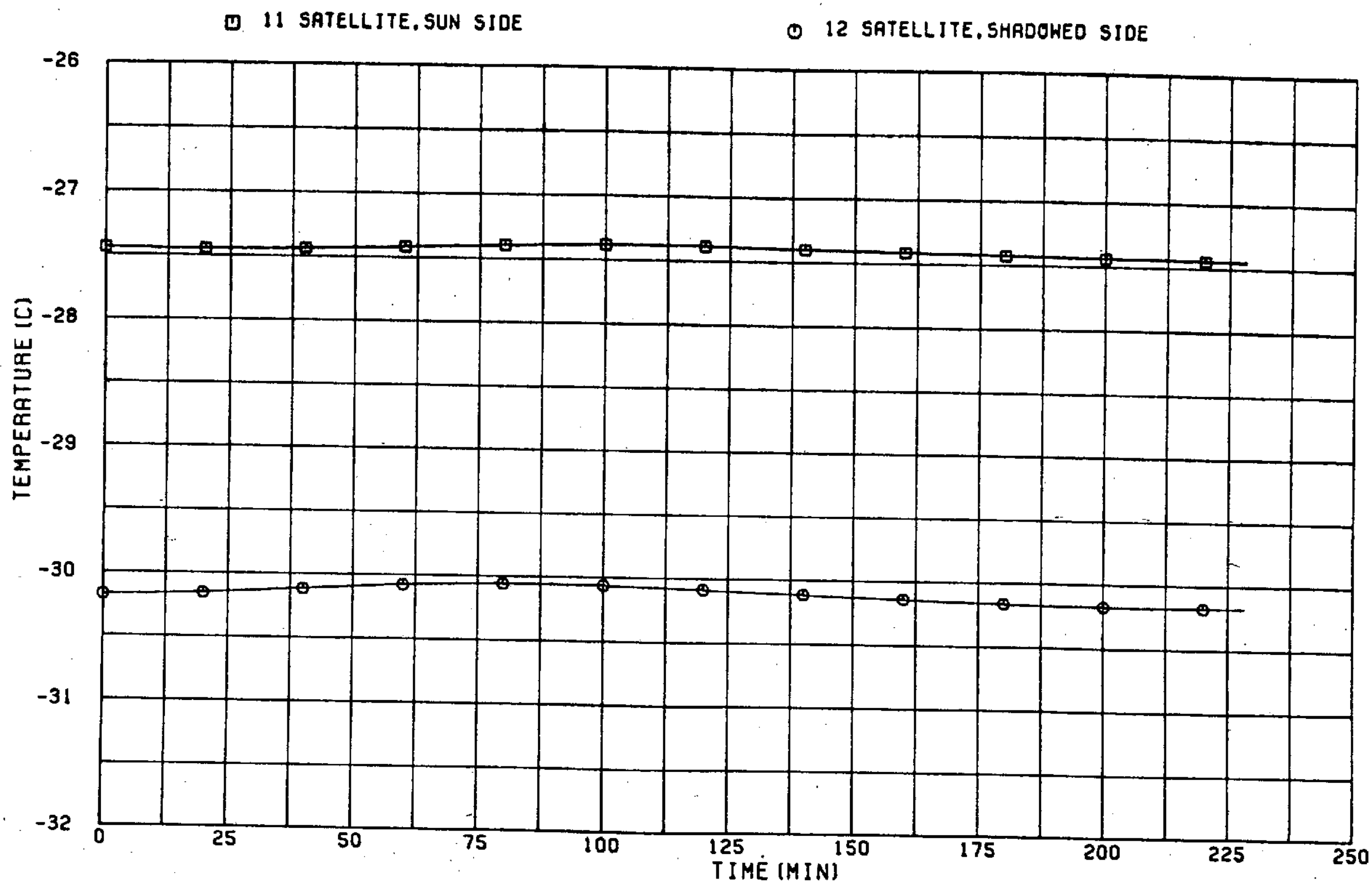
1. The average satellite core temperature is approximately -29° C.

2. The total satellite core temperature fluctuation, during the orbit duration, is within 1/4° C.

3. The temperature gradient across the aluminum structure is approximately 3° C,for a non-spinning satellite.

SATELLITE STRUCTURE STABILIZATION TEMPERATURES

HEXAGONAL CORNER, FACE FLUSH WITH SURFACE, Z-93 COATING (.2/.9), FULL SUN
LAGEOS 01 RUN DATE 04/03/74



BENDIX AEROSPACE SYSTEMS DIVISION

TYPICAL CORNER TEMPERATURE RESPONSES

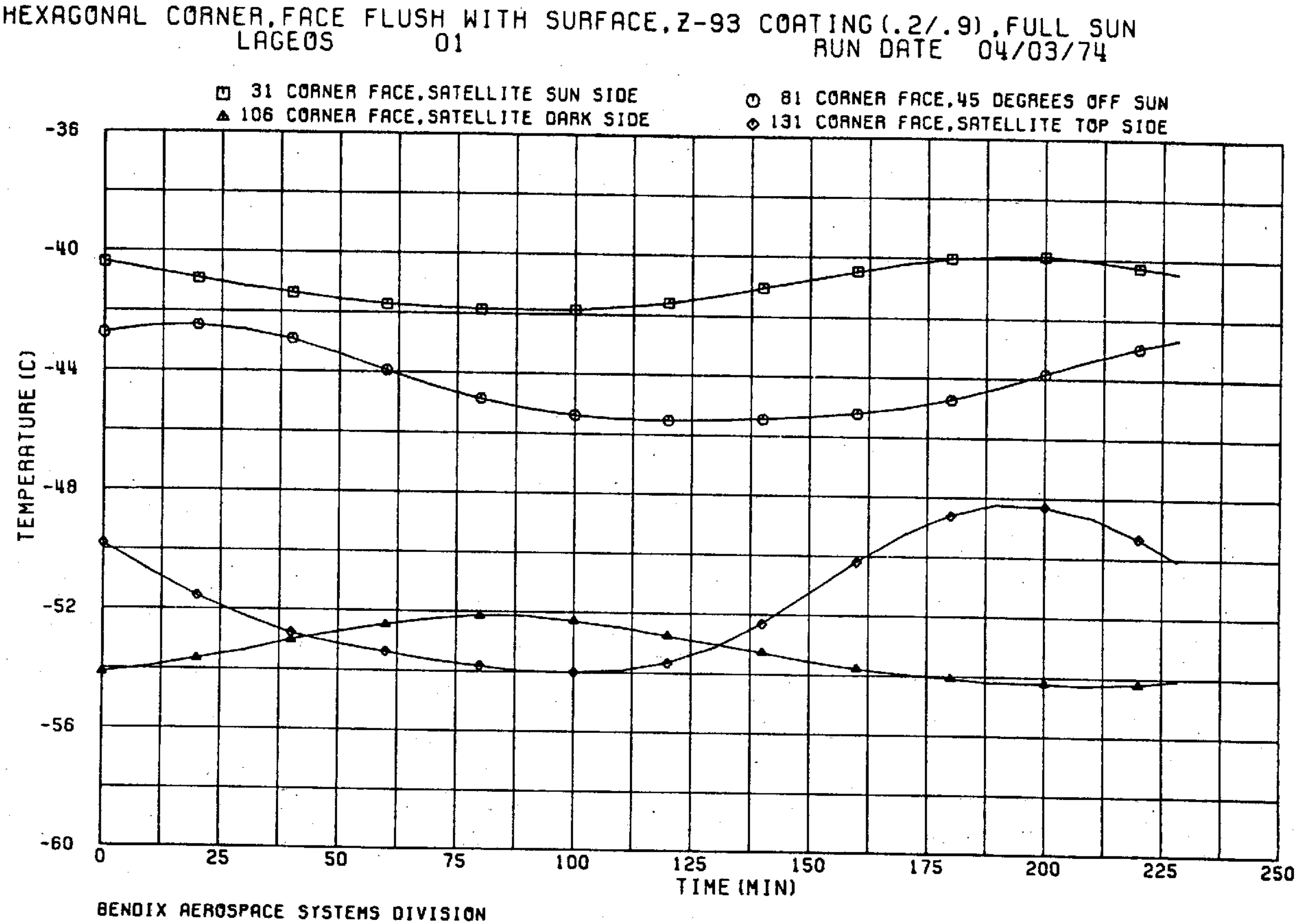
Typical corner temperature responses at various corner locations on the satellite, for the indicated conditions, are shown. The conclusions are:

1. All corner temperatures range between -54 and -40°C.

2. At any instant, the maximum temperature difference between corners is approximately 14°C.

3. The maximum temperature fluctuation per corner for the orbit duration is 6°C (corner located on satellite top surface.)

TYPICAL CORNER TEMPERATURE RESPONSES

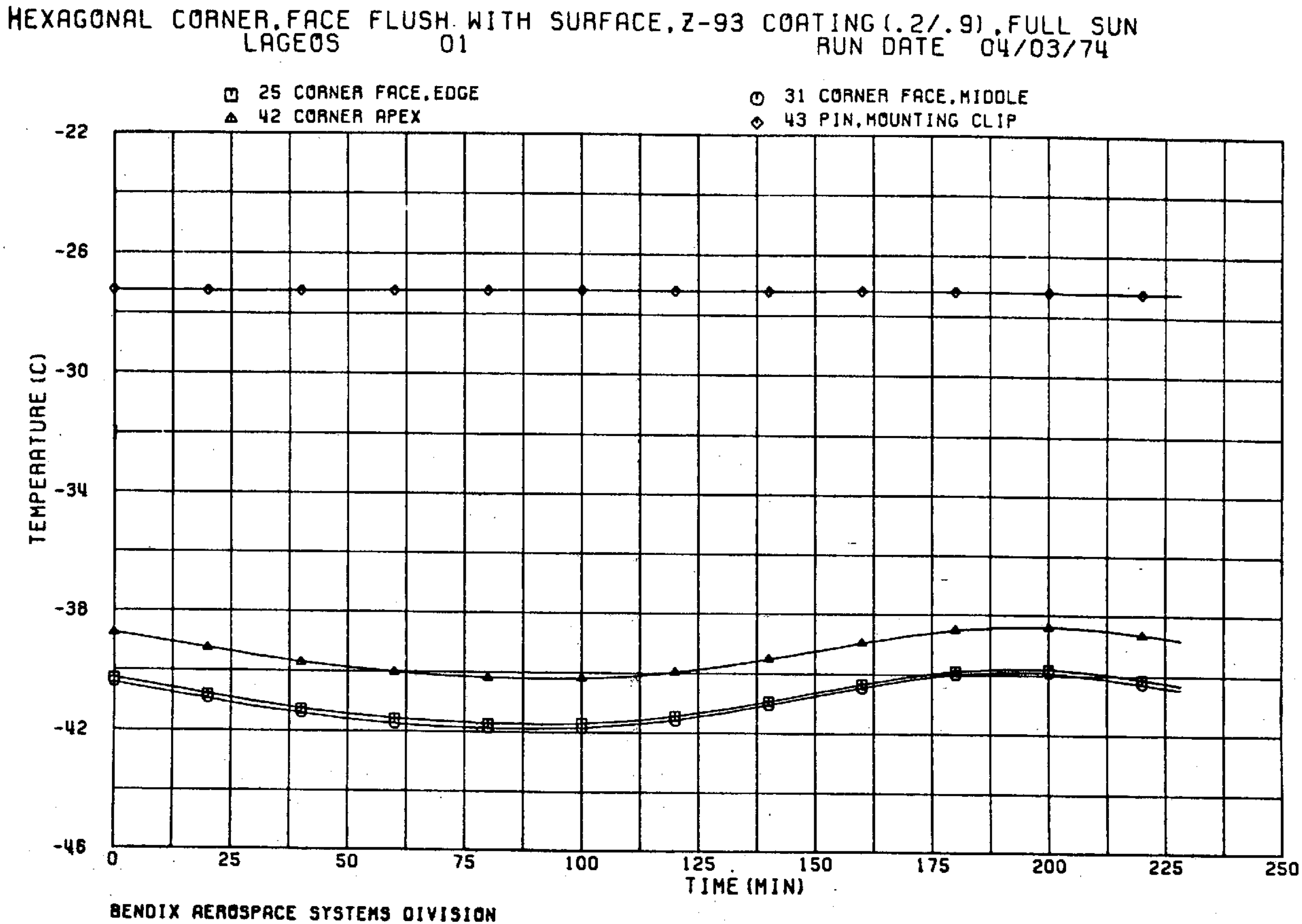


WORST CASE CORNER TEMPERATURE DISTRIBUTIONS

Temperature responses for the retroreflector oriented toward the sun, corresponding to the noted conditions, are described. The summarized results are:

1. The average mounting clip-to-retroreflector temperature difference is 13°C.
2. The corner maximum axial temperature gradient is 1.7°C.
3. The corner maximum radial temperature gradient is 0.2°C.
4. Both the axial and radial temperature gradients are approximately constant over the orbit duration.

WORST CASE CORNER TEMPERATURE DISTRIBUTIONS



SUMMARY OF HEX-FACED RETROREFLECTOR AND Z-93 THERMAL CONTROL COATING

Maximum axial and radial temperature gradients are tabulated for five retroreflectors at various locations on the satellite. Temperature gradients shown correspond to the hexagonal-faced retroreflector, with the face flush with the satellite surface and with Z-93 coating applied. The average maximum corner axial and radial temperature gradients are approximately the same for all corners.

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SUMMARY OF THERMAL DESIGN/ANALYSIS
HEXAGONAL FACE RETROREFLECTOR, Z-93 THERMAL COATING*

Location	Corner #1 Normal to Sun	Corner #2 16° Off-Sun	Corner #3 45° Off-Sun	Corner #4 180° Off-Sun	Corner #5 90° Off-Sun	Average
ΔT_{Axial} (°C)	1.74	1.75	1.66	1.66	1.70	1.70
ΔT_{Radial} (°C)	0.19	0.20	0.19	0.33	0.35	0.25

* Z-93 THERMAL/OPTICAL PROPERTIES = α_s/ϵ_{ir} = 0.2/0.9

SUMMARY OF HEX-FACED RETROREFLECTOR AND VDA THERMAL CONTROL COATING

For the second thermal design condition, vacuum deposited aluminum (VDA) was assumed on the satellite. All other configuration and environmental factors remain the same as the previously considered case. The average core temperature for the VDA condition is +2°C, versus -29°C for the Z-93 case. The application of VDA coating induces maximum gradients of 2.79 and 0.44°C, respectively.

SUMMARY OF THERMAL DESIGN/ANALYSIS
HEXAGONAL FACE RETROREFLECTOR, VDA THERMAL COATING*

Location	Corner #1 Normal to Sun	Corner #2 16° Off-Sun	Corner #3 45° Off-Sun	Corner #4 180° Off-Sun	Corner #5 90° Off-Sun	Average
ΔT Axial (°C)	2.84	2.83	2.72	2.76	2.79	2.79
ΔT Radial (°C)	0.40	0.39	0.40	0.52	0.51	0.44

* VDA THERMAL/OPTICAL PROPERTIES = α_s/ϵ_{ir} = 0.15/0.05

SUMMARY - HEXAGONAL-FACED RETROREFLECTOR AND THERMAL CONTROL COATINGS

A direct thermal/optical performance comparison between the Z-93 and VDA coatings is shown. The results show that the optical performance for LAGEOS will be degraded if coatings possessing high α/ϵ ratios are used. If the LAGEOS corner is assumed to perform the same as a perfect -90° retroreflector, based on ALSEP program data, its relative central irradiance would decrease from about 70 to 38%, corresponding to Z-93 and VDA, respectively. Although relative central irradiance is not a performance parameter of interest in LAGEOS, it is used only as a means of comparing relative performance. These results show that the LAGEOS optical performance will be influenced by the type of thermal control coating/finish applied to the satellite exterior surface.

LAGEOS
SUMMARY OF THERMAL DESIGN/ANALYSIS
HEXAGONAL FACE RETROREFLECTOR
COMPARISON OF THERMAL CONTROL COATINGS

THERMAL COATING	Z - 93	VDA
ΔT_{Axial} (°C)	1.70	2.79
ΔT_{Radial} (°C)	0.25	0.44
RELATIVE CENTRAL IRRADIANCE*	70%	38%

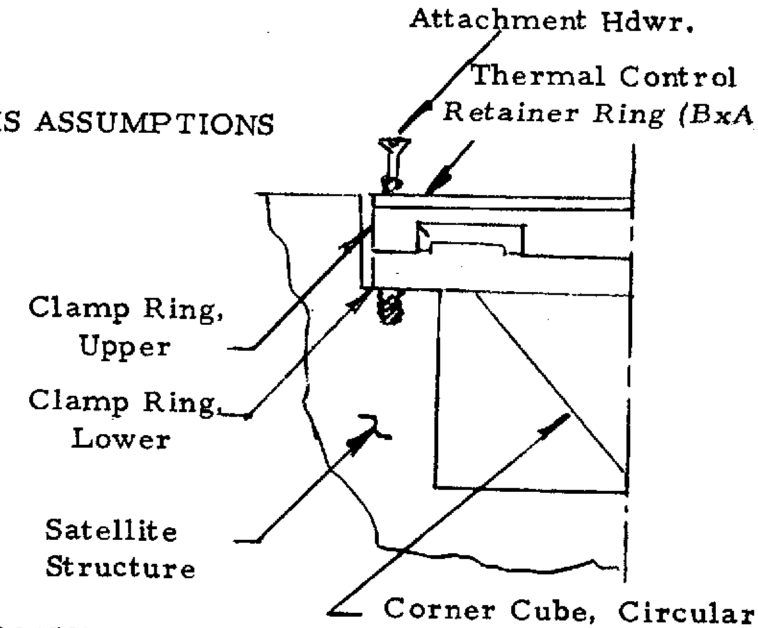
* BASED ON PRELIMINARY ALSEP THERMAL/OPTICAL PERFORMANCE ESTIMATES.

CIRCULAR CORNER THERMAL DESIGN/ANALYSIS ASSUMPTIONS

The circular-faced retroreflector, and its associated mounting configuration, constituted the third thermal analysis condition investigated. The corner is held in the cavity by its three mounting tabs which are captured between two Kel- F rings. A 6061-T6 aluminum ring and three #2-56 flat head screws provide structural attachment of the Kel- F rings to the satellite. A gap is provided between the rings and the corner tab to provide conductive isolation between the retroreflector and the satellite structure. The retroreflector front-face was assumed to be flush with the satellite surface. Z-93 thermal control coating was assumed to be applied to the satellite outside surface and to the thermal control retainer ring exterior surfaces.

LAGEOS

CIRCULAR CORNER THERMAL DESIGN/ANALYSIS ASSUMPTIONS



- CORNER CUBE, CIRCULAR (DWG NO. 50M24461).
- CLAMP RING, LOWER (DWG NO. 50M24459, P/N 1).
- CLAMP RING, LOWER (DWG NO. 50M24459, P/N 2).
- SATELLITE STRUCTURE, HALF SPHEIZE CONCEPT (DWG NO. 30M20453).

  EXTERIOR SURFACE: 7-10 MILS Z-93 (α_s/ϵ_{ir} = 0.2/0.9).

  INTERIOR SURFACE: BARE MACHINED ALUMINUM, CLEANED AND DEGREASED (ϵ_{ir} = 0.05).

- ATTACHMENT HARDWARE

  #2-56, 316 S/S FLAT HEAD SCREW WITH LOCKING HELICOIL INSERT

  TORQUED TO 2.5 IN LBS AND BACKED-OFF TWO TURNS TO PROVIDE AN APPROXIMATE 0.030 INCH "FLOAT" (MINIMIZES CONTACT PRESSURE).

- THERMAL CONTROL RETAINER RING (BXA ADDITION TO MSFC DESIGN)

  PROVIDES TEMPERATURE CONTROL FOR UPPER CLAMP RING.

  AFFORDS STRUCTURAL SUPPORT FOR KEL "F" MATERIAL DURING MECHANICAL LOADING.

SATELLITE STRUCTURE STABILIZATION TEMPERATURES - CIRCULAR CORNER

Satellite core temperatures for the circular-faced corner, mounted flush with the satellite surface and with Z-93 coating applied, are presented. The highlights are as follows:

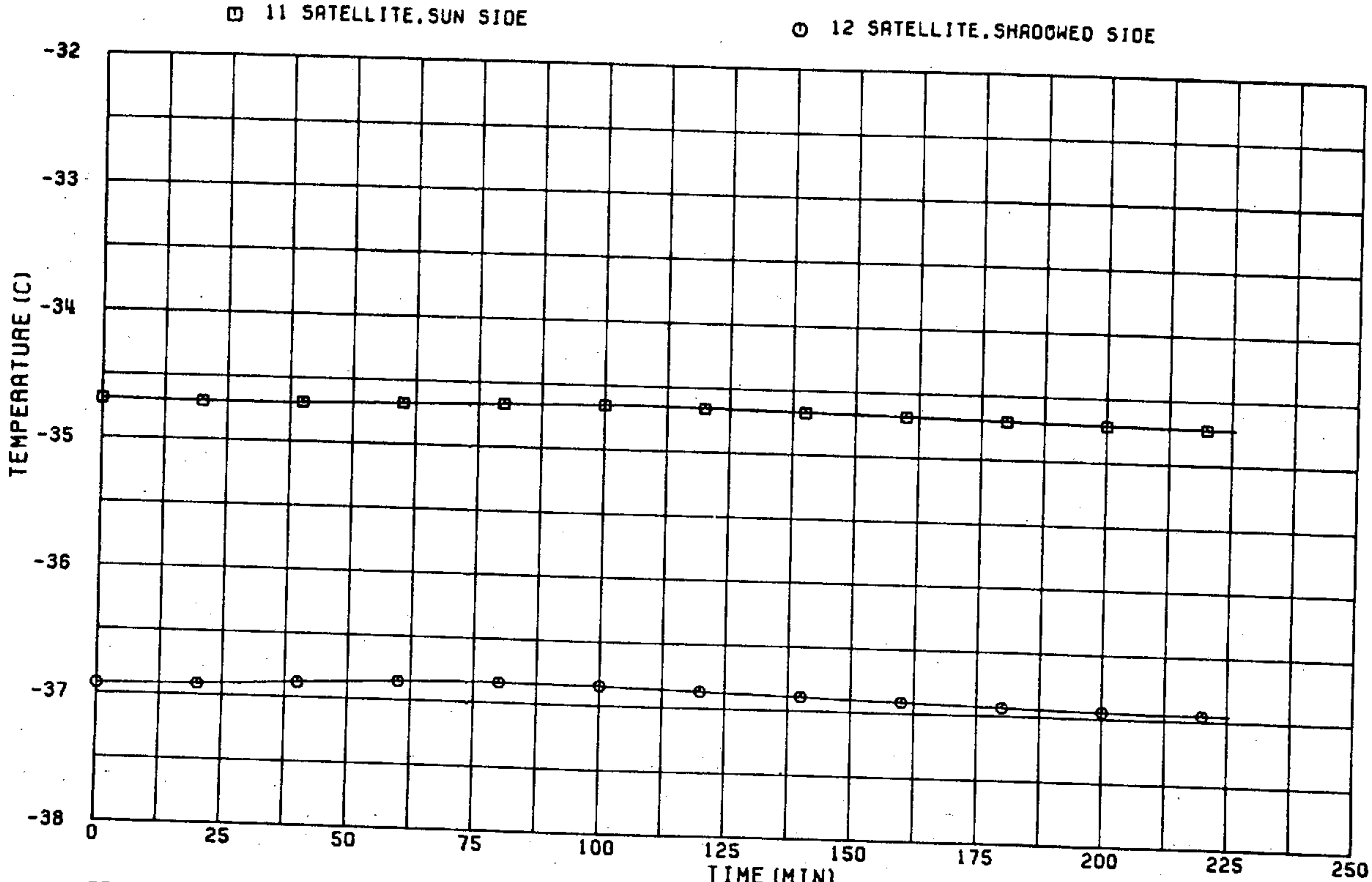
1. The average satellite core temperature is approximately -36°C.

2. The total satellite core temperature fluctuation during the orbit duration is within 1/4°C.

3. The temperature gradient across the aluminum structure is approximately 2°C for a non-spinning satellite.

SATELLITE STRUCTURE STABILIZATION TEMPERATURES

CIRCULAR CORNER, FACE FLUSH WITH SURFACE, Z-93 COATING (.2/.9), FULL SUN
LAGEOS 03
RUN DATE 04/04/74



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TYPICAL CORNER TEMPERATURE RESPONSES - CIRCULAR CORNER

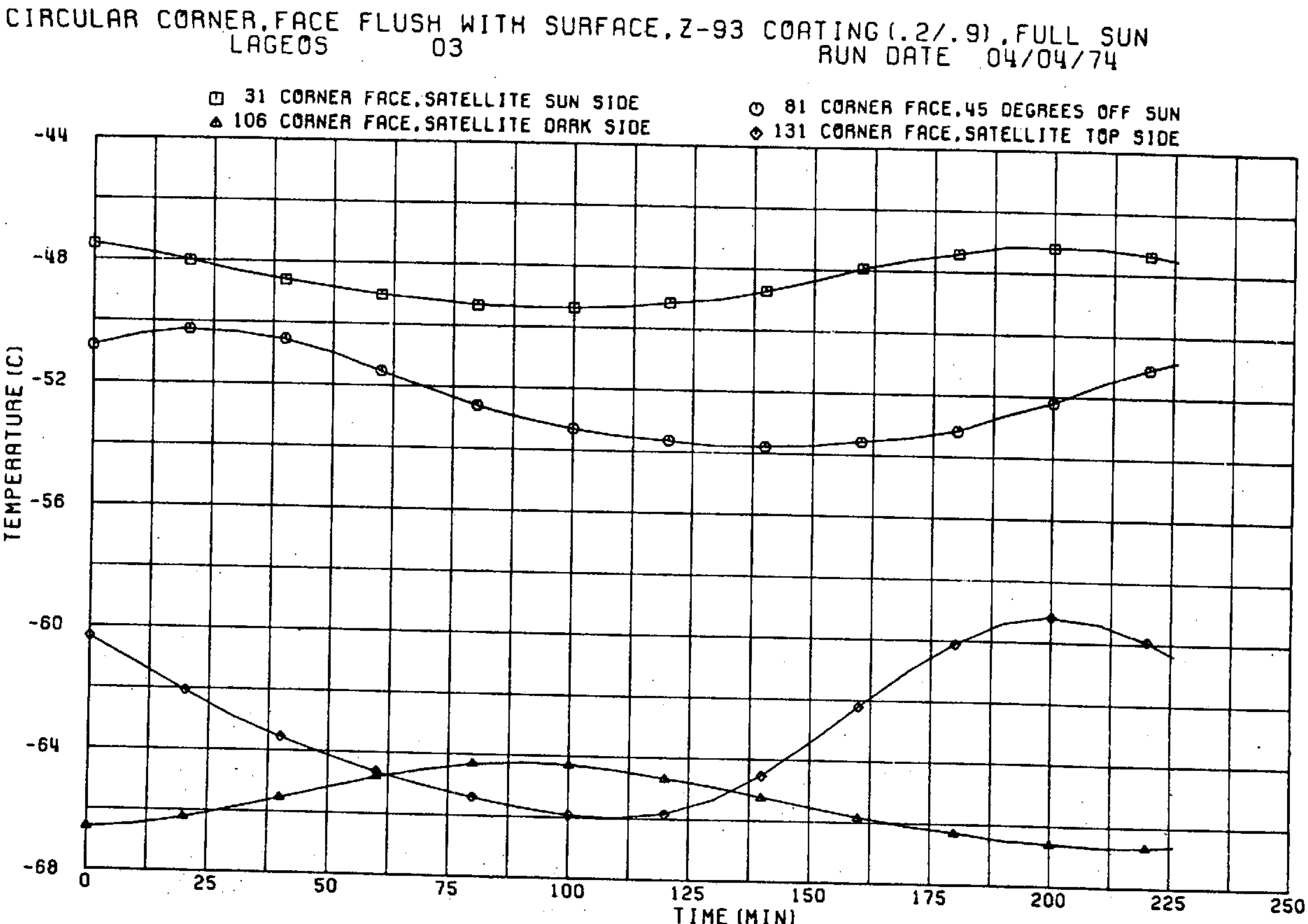
Typical corner temperature responses at various locations on the satellite, for the indicated conditions, are shown. The conclusions are:

1. All corner temperatures range between -67 and 47°C.

2. At any instant, the maximum temperature difference between corners is approximately 20°C.

3. The maximum temperature fluctuation, per corner, for the orbit duration is -7°C (in the corner located on the satellite top surface.)

TYPICAL CORNER TEMPERATURE RESPONSES



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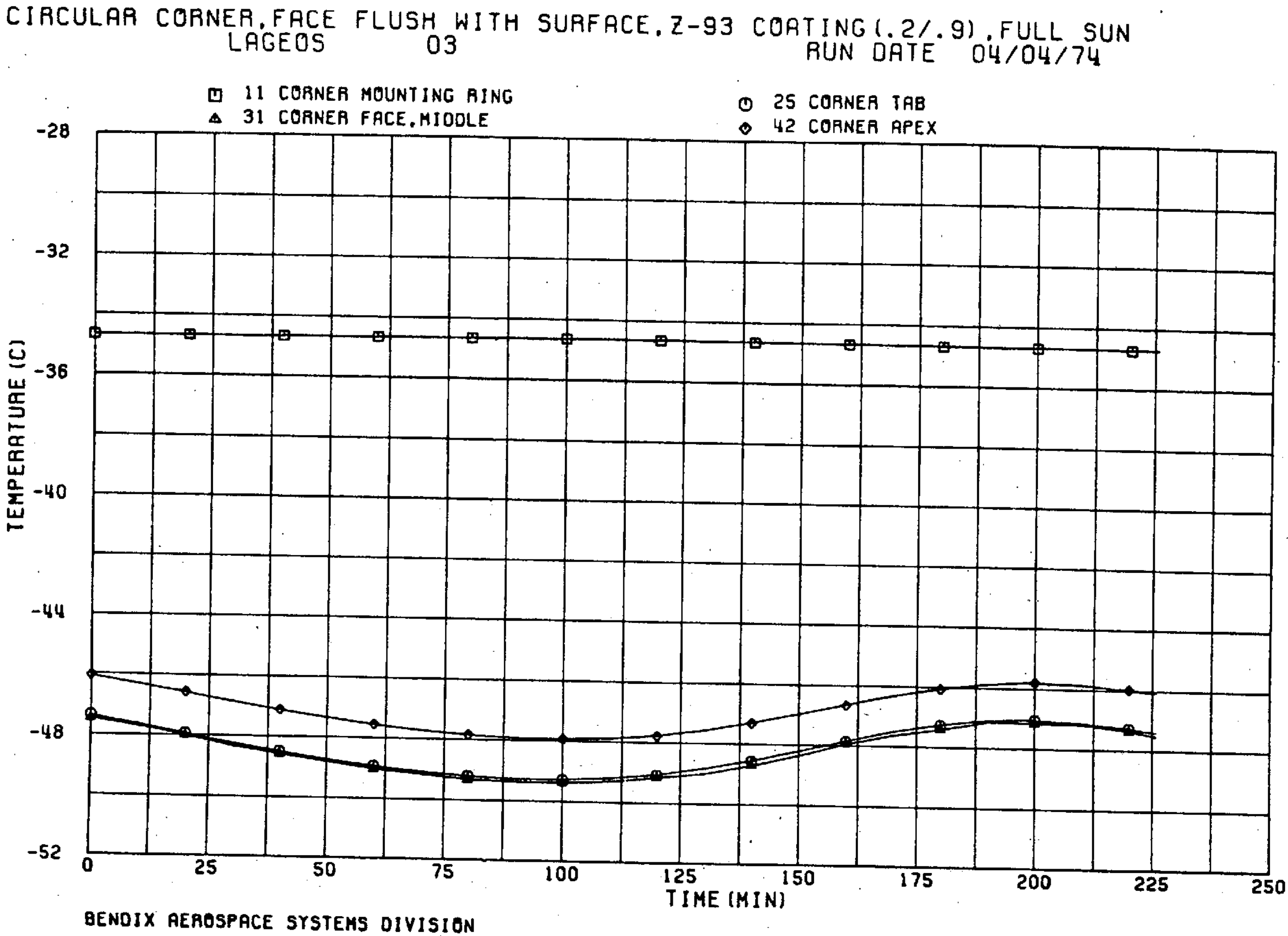
WORST-CASE CORNER TEMPERATURE DISTRIBUTIONS - CIRCULAR CORNER

Temperature responses for the retroreflector oriented toward the sun, corresponding to the noted conditions, are shown. The summarized results are:

1. The average mounting ring-to-retroreflector temperature difference is $13^{\circ}C$.
2. The corner maximum axial temperature gradient is $1.5^{\circ}C$.
3. The corner maximum radial temperature gradient is $0.2^{\circ}C$.
4. Both the axial and radial temperature gradients are approximately constant over the orbit duration.

WORST CASE CORNER TEMPERATURE DISTRIBUTIONS



SUMMARY OF CIRCULAR-FACED RETROREFLECTOR AND Z-93 THERMAL CONTROL COATING

Maximum axial and radial temperature gradients are tabulated for five retroreflectors mounted at various locations on the satellite. Temperature gradients shown correspond to the circular-faced retroreflector, with the face flush with the satellite surface and with Z-93 coating applied. The average maximum corner axial and radial temperature gradients are 1.55 and 0.20°C, respectively. Maximum temperature gradients are approximately the same for all corners.

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SUMMARY OF THERMAL DESIGN ANALYSIS
CIRCULAR FACE RETROREFLECTOR, Z-93 THERMAL COATING*

Location	Corner #1 Normal to Sun	Corner #2 16° Off-Sun	Corner #3 45° Off-Sun	Corner #4 180° Off-Sun	Corner #5 90° Off-Sun	Average
ΔT_{Axial} (°C)	1.55	1.53	1.50	1.58	1.58	1.55
ΔT_{Radial} (°C)	0.16	0.19	0.18	0.24	0.25	0.20

* Z-93 THERMAL OPTICAL PROPERTIES = $\alpha s/\epsilon ir$ = 0.2/0.9

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COMPARISON OF HEX AND CIRCULAR RETROREFLECTORS (Z-93 THERMAL CONTROL COATING)

A direct comparison of thermal/optical performance for the hexagonal and circular retroreflectors is presented. All environmental aspects are the same and the only differences are the retroreflector configurations and their associated mounting hardware. Maximum average axial temperature gradients for the hexagonal and circular retroreflectors are 1.70 and 1.55°C, respectively. Maximum average radial temperature gradients for the hexagonal and circular retroreflectors are 0.25 and 0.20°C respectively. If the LAGEOS corner is assumed to perform the same as a perfect -90° (ALSEP-type) retroreflector, based on ALSEP program data, the relative central irradiance for the hexagonal and circular configurations would be 70 and 78%, respectively. As described in a previous chart, relative central irradiance is used here only as a means of comparing relative performance. The actual effects of thermal gradients on LAGEOS performance parameters are to be determined later in this Phase B program.

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SUMMARY OF THERMAL DESIGN/ANALYSIS
Z-93 THERMAL CONTROL COATING
COMPARISON OF HEXAGONAL AND CIRCULAR CORNERS

CORNER TYPE	HEXAGONAL	CIRCULAR
ΔT_{Axial} (°C)	1.70	1.55
ΔT_{Radial} (°C)	0.25	0.20
RELATIVE CENTRAL IRRADIANCE*	70%	78%

* BASED ON PRELIMINARY ALSEP THERMAL/OPTICAL PERFORMANCE ESTIMATES

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SELECTION OF THE RETROREFLECTOR CONFIGURATION - THERMAL OPTICAL VIEWPOINT

The thermal analysis has shown the circular retroreflector to be approximately 11% better optically than its hexagonal counterpart. However, the laser impingement (frontface) area is about 10% larger for the hexagonal-faced retroreflector. It is believed that the superior optical performance of the circular-faced retroreflector may be counter balanced, to some extent, by the greater laser impingement area of the hexagonal-faced retroreflector. Considering all factors, there is little thermal/optical performance difference between the two retroreflector configuration candidates.

LAGEOS
SELECTION OF RETROREFLECTOR CONFIGURATION
FROM THERMAL/OPTICAL VIEWPOINT

- 11%* OPTICAL PERFORMANCE IMPROVEMENT FOR CIRCULAR RETROREFLECTOR OVER THE HEXAGONAL RETROREFLECTOR.

- FRONT FACE AREA FOR THE HEXAGONAL RETROREFLECTOR IS APPROXIMATELY 10% LARGER THAN THAT FOR THE CIRCULAR RETROREFLECTOR.

- SUPERIOR THERMAL PERFORMANCE OF CIRCULAR RETRO-REFLECTOR IS COUNTERBALANCED BY INCREASED FACE AREA OF HEXAGONAL RETROREFLECTOR.

- THERE IS MINIMAL OPTICAL PERFORMANCE DIFFERENCE BETWEEN THE HEXAGONAL AND CIRCULAR RETROREFLECTORS.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations of the LAGEOS thermal design/analysis, as conducted to date, are:

1. On the basis of thermal/optical performance, the circular and hexagonal retroreflectors are approximately equivalent.

2. It is essential to, radiatively and conductively, decouple the retroreflector from its mounting cavity to minimize temperature gradients.

3. Thermal control coatings which minimize the satellite core temperature will also minimize retroreflector temperature gradients. For this reason, coatings/finishes having stable values of low solar absorptance and high IR emittance are required for optimum performance.

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CONCLUSIONS AND RECOMMENDATIONS

- OPTICAL PERFORMANCE FOR THE CIRCULAR AND HEXAGONAL RETROREFLECTORS ARE APPROXIMATELY EQUIVALENT.
- LAGEOS OPTIMUM THERMAL DESIGN WILL RADIATIVELY AND CONDUCTIVELY ISOLATE THE RETROREFLECTORS FROM THE SATELLITE STRUCTURE.
- IDEAL THERMAL CONTROL COATINGS WILL POSSESS STABLE PROPERTIES OF LOW SOLAR ABSORPTANCE AND HIGH IR EMITTANCE.

POTENTIAL THERMAL CONTROL COATINGS

Typical state-of-the-art passive thermal control coatings, which are suitable for LAGEOS, are tabulated. The leading contenders appear to be IIT's Z-93 and clear anodize, in that order. The advantages and disadvantages of each coating are listed.

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POTENTIAL THERMAL CONTROL COATINGS

COATING/FINISH*	THERMAL/OPTICAL PROPERTIES ($\alpha s/\epsilon ir$)	ADVANTAGES	DISADVANTAGES
CLEAR SULFURIC ACID ANODIZE	0.52/0.86	INITIAL PROPERTIES ARE SATISFACTORY; EASY TO APPLY.	UNSTABLE, αs DEGRADES TO 0.72 AFTER ONE YEAR EXPOSURE TO UV.
GRIT BLASTED	0.46/0.30	STABLE THERMAL/ OPTICAL PROPERTIES.	PROPERTIES ARE NOT OPTIMUM FOR LAGEOS.
VDA/SiO	0.15/0.60	DESIRABLE PROPERTIES; NO DEGRADATION.	DIFFICULT TO APPLY; EXTREMELY FRAGILE.
ITT'S Z-93	0.2/0.9	DESIRABLE PROPERTIES; PREVIOUSLY FLOWN ON ALSEP LR^3 MISSIONS; STABLE, αs DEGRADES TO 0.30 AFTER ONE YEAR EXPOSURE.	DIFFICULT TO APPLY AND TO KEEP CLEAN.
PORCELAIN/ENAMEL	0.26/0.85	DESIRABLE PROPERTIES; STABLE.	DIFFICULT TO APPLY, NO FLIGHT PERFORMANCE DATA.

*COMPATIBLE WITH 6061-T6 ALUMINUM SUBSTRATE.

FUTURE THERMAL DESIGN/ANALYSIS WORK

It is necessary that baseline thermal control coating characteristics be selected for the LAGEOS Phase B effort at this time. Further analysis effort can then be conducted. Other areas of future thermal analysis effort to be performed are also listed.

LAGEOS
FUTURE THERMAL DESIGN/ANALYSIS WORK

- INVESTIGATE RECESSION OF RETROREFLECTOR INTO SATELLITE STRUCTURE UP TO A DEPTH OF ONE CENTIMETER.
- SELECT THERMAL CONTROL COATING(S) FOR LAGEOS AND DETERMINE EFFECTS OF THERMAL/OPTICAL PROPERTY DEGRADATION ON SATELLITE OPTICAL PERFORMANCE.
- DEVELOP A TEST ITEM/CHAMBER THERMAL MATH MODEL TO DETERMINE RETROREFLECTOR HEATING/COOLING RATES, TEMPERATURE STABILIZATION TIMES, AND TEST ITEM TEMPERATURE LEVELS.
- PROVIDE ITEK WITH RETROREFLECTOR TEMPERATURE DISTRIBUTIONS TO PERMIT OPTICAL PERFORMANCE PREDICTIONS.

Bendix Aerospace Systems Division

LAGEOS

STRUCTURAL/DYNAMIC DESIGN AND ANALYSIS

J. Maszatics

17 April 1974

Updated 1 June 1974

This chart presents a brief description of the math model used for the structural analyses of the LAGEOS hex-faced CCR/support clip assembly.

STRUCTURAL ANALYSIS MATHEMATICAL MODEL OF A SINGLE CCR/SUPPORT CLIP ASSEMBLY

- THIRTY-ONE (31) NODES
- THIRTEEN (13) SOLID ELEMENTS
- TWENTY-FOUR (24) BEAM ELEMENTS
- ONE PERCENT (1%) CRITICAL DAMPING
- TOTAL RESTRAINTS (BUILT-IN) AT NODES 29, 30, & 31
- NO MOMENTS NOR AXIAL LOADS AT NODES 14, 15 & 16

<u>CCR</u> - 13 SOLID ELEMENTS (TETRAHEDRONS)
- 9 RIGID-MASSLESS BEAMS

<u>CLIP</u> - 15 BEAM ELEMENTS

The following group of charts define the math-model for the LAGEOS structural analyses.

The Nodal Coordinate Table lists the rectilinear coordinates (in centimeters) of the 31 math-model nodes. The origin of the coordinate system is at the CCR apex, with the x3-axis perpendicular to the CCR hex-face, the x2-axis parallel to the hex-face and perpendicular to a pair of sides on the hex-face, and the remaining x1-axis completing the triad.

The Tetrahedron Input Table locates the solid elements by listing the four nodes (by node number) that are the four corners of each tetrahedron. Also, listed are the modulus of elasticity (gm/cm^2), Poissons ratio, and the coefficient of thermal expansion ($cm/cm/^oC$) for the tetra-
hedron material (quartz).

The Material Property Table lists the modulus of elasticity (gm/cm^2), Poissons ratio, density (gm/cm^3) and the coefficient of thermal expansion ($cm/cm/^oC$) for all materials used in the model.

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CDC/MRI STARDYNE MATHEMATICAL MODEL FOR LAGEOS

*** NODAL COORDINATE TABLE ***

	NODE	X1	X2	X3
NODES	1	0.	0.	0.
NODES	2	-.1900000E+01	0.	.1343500E+01
NODES	3	.9500000E+00	.1645450E+01	.1343500E+01
NODES	4	.9500000E+00	-.1645450E+01	.1343500E+01
NODES	5	0.	-.2193930E+01	.2712010E+01
NODES	6	-.1900000E+01	-.1096970E+01	.2712010E+01
NODES	7	-.1900000E+01	.1096970E+01	.2712010E+01
NODES	8	0.	.2193930E+01	.2712010E+01
NODES	9	.1900000E+01	.1096970E+01	.2712010E+01
NODES	10	.1900000E+01	-.1096970E+01	.2712010E+01
NODES	11	.9500000E+00	.1645450E+01	.2712010E+01
NODES	12	.9500000E+00	-.1645450E+01	.2712010E+01
NODES	13	-.1900000E+01	0.	.2712010E+01
NODES	14	-.1750140E+01	0.	.2077010E+01
NODES	15	.8750700E+00	.1515670E+01	.2077010E+01
NODES	16	.8750700E+00	-.1515670E+01	.2077010E+01
NODES	17	-.1963500E+01	0.	.2077010E+01
NODES	18	.9817500E+00	.1700440E+01	.2077010E+01
NODES	19	.9817500E+00	-.1700440E+01	.2077010E+01
NODES	20	-.1963500E+01	0.	.1414070E+01
NODES	21	.9817500E+00	.1700440E+01	.1414070E+01
NODES	22	.9817500E+00	-.1700440E+01	.1414070E+01
NODES	23	-.1963500E+01	0.	.7511300E+00
NODES	24	.9817500E+00	.1700440E+01	.7511300E+00
NODES	25	.9817500E+00	-.1700440E+01	.7511300E+00
NODES	26	-.1963500E+01	0.	.8819000E-01
NODES	27	.9817500E+00	.1700440E+01	.8819000E-01
NODES	28	.9817500E+00	-.1700440E+01	.8819000E-01
NODES	29	-.1963500E+01	0.	-.5747500E+00
NODES	30	.9817500E+00	.1700440E+01	-.5747500E+00
NODES	31	.9817500E+00	-.1700440E+01	-.5747500E+00

*** TETRAHEDRON INPUT TABLE ***

TETRA	V1	V2	V3	V4	E	POIS	ALPHA
1	1	2	3	4	.717000E+09	.170000E+00	.550000E-06
2	2	3	4	12	.717000E+09	.170000E+00	.550000E-06
3	3	11	12	13	.717000E+09	.170000E+00	.550000E-06
4	2	3	12	13	.717000E+09	.170000E+00	.550000E-06
5	2	4	6	13	.717000E+09	.170000E+00	.550000E-06
6	4	5	6	12	.717000E+09	.170000E+00	.550000E-06
7	4	6	12	13	.717000E+09	.170000E+00	.550000E-06
8	3	2	8	11	.717000E+09	.170000E+00	.550000E-06
9	2	7	8	13	.717000E+09	.170000E+00	.550000E-06
10	2	8	13	11	.717000E+09	.170000E+00	.550000E-06
11	4	3	10	12	.717000E+09	.170000E+00	.550000E-06
12	3	9	10	11	.717000E+09	.170000E+00	.550000E-06
13	3	10	11	12	.717000E+09	.170000E+00	.550000E-06

*** MATERIAL PROPERTY TABLE ***

NO	NAME	E	POIS. RATIO	DENSITY	ALPHA
1	QUARTZ	.717000E+09	.170000E+00	.220000E+01	.550000E-06
2	BE CU	.133600E+10	.330000E+00	.822000E+01	.167000E-04

The Beam Section Property Table lists the area (cm^2), torsional moment of inertia (cm^4), and both cross-sectional moments of inertia (cm^4) for each beam type used in the model.

The Beam Connectivity Table numbers each beam, defines its location by its end points (node numbers), defines its orientation (JC), lists the material and beam property by number, lists the width, thickness (H2 and H3) and length (cm) of each beam, and re-iterates the section properties given in the previous table. The "pin code" retains (0) or releases (1) the capability of beam ends to resist forces and moments. The "111100", at beams 1, 2, and 3, limits the mounting pins to provide only lateral forces to restrain the motion of the CCR. This condition is the closest approximation to the actual loading expected.

The Nodal Constraint Table lists the motion constraints, denoted by (1), imposed at certain nodes. Nodes 29, 30, and 31 are fully restrained—no translations nor rotations are allowed. These nodes represent the base of the support clip which is assumed to be "built-in".

CDC/MRI STARDYNE MATHEMATICAL MODEL FOR LAGEOS

*** BEAM SECTION PROPERTY TABLE ***

NO	A	J	I2	I3	SF2	SF3
1	.170000E-01	.461000E-04	.231000E-04	.231000E-04	-0.	-0.
2	.565200E-01	.472000E-04	.582900E-02	.121500E-04	-0.	-0.
3	0.	.100000E+01	.100000E+01	.100000E+01	-0.	-0.

*** BEAM CONNECTIVITY TABLE ***

	NO	JA	JB	JC	MATL NO	BPRP NO	PIN CODE	H2	H3	LENGTH	AREA	J	I2	I3	SF2	SF3
BEAM	1	14	17	0	2	1	111100	1.470E-01	1.470E-01	2.134E-01	1.700E-02	4.610E-05	2.310E-05	2.310E-05	-0.	-0.
BEAM	2	15	18	0	2	1	111100	1.470E-01	1.470E-01	2.134E-01	1.700E-02	4.610E-05	2.310E-05	2.310E-05	-0.	-0.
BEAM	3	16	19	0	2	1	111100	1.470E-01	1.470E-01	2.134E-01	1.700E-02	4.610E-05	2.310E-05	2.310E-05	-0.	-0.
BEAM	4	17	20	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	5	18	21	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	6	19	22	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	7	14	2	0	1	3	000000	-0.	-0.	7.487E-01	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	8	14	6	0	1	3	000000	-0.	-0.	1.276E+00	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	9	14	7	0	1	3	000000	-0.	-0.	1.276E+00	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	10	15	3	0	1	3	000000	-0.	-0.	7.487E-01	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	11	15	8	0	1	3	000000	-0.	-0.	1.276E+00	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	12	15	9	0	1	3	000000	-0.	-0.	1.276E+00	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	13	16	4	0	1	3	000000	-0.	-0.	7.487E-01	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	14	16	5	0	1	3	000000	-0.	-0.	1.276E+00	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	15	16	10	0	1	3	000000	-0.	-0.	1.276E+00	0.	1.000E+00	1.000E+00	1.000E+00	-0.	-0.
BEAM	16	20	23	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	17	21	24	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	18	22	25	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	19	23	26	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	20	24	27	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	21	25	28	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	22	26	29	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	23	27	30	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.
BEAM	24	28	31	1	2	2	000000	5.080E-02	1.112E+00	6.629E-01	5.652E-02	4.720E-05	5.829E-03	1.215E-05	-0.	-0.

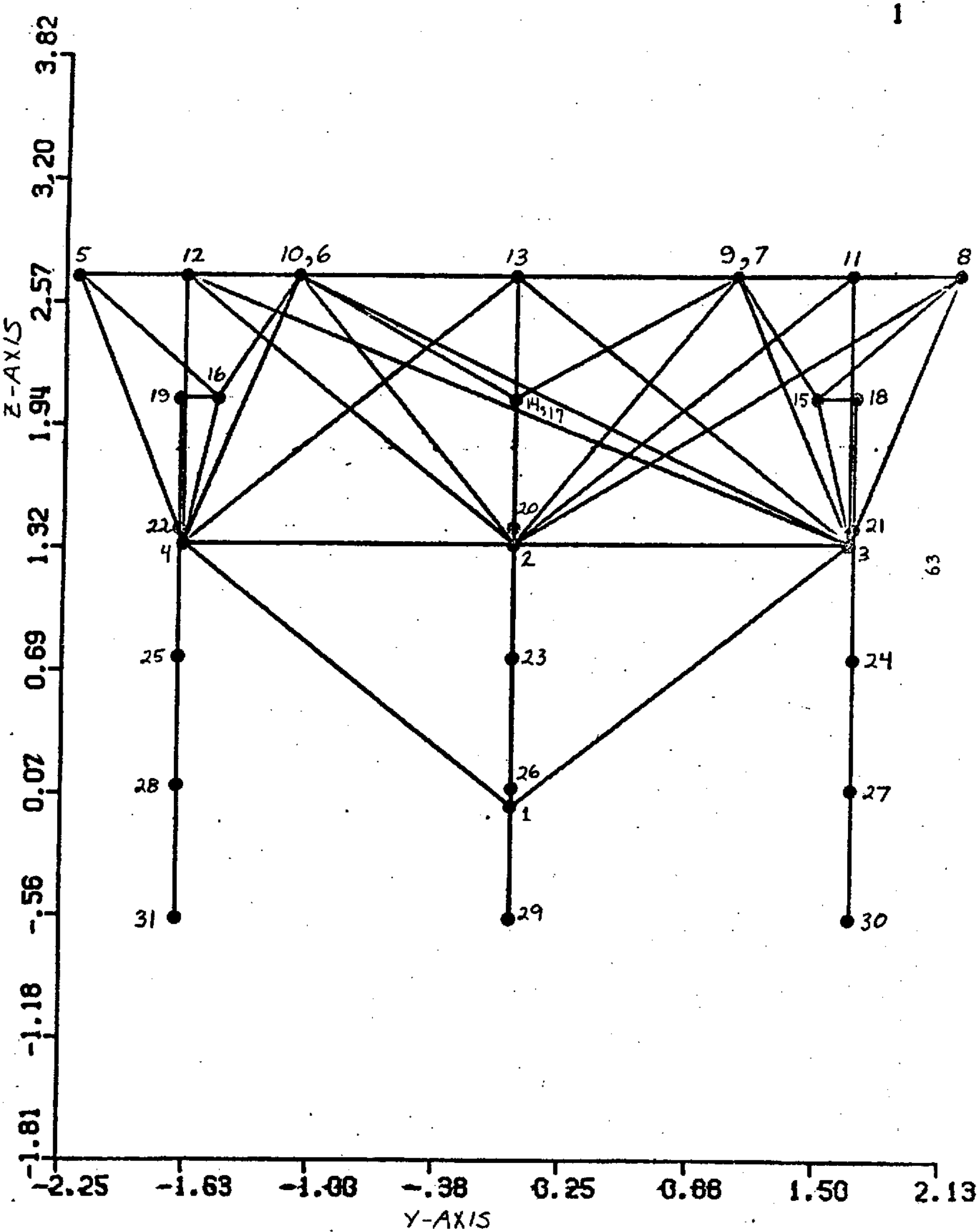
*** NODAL RESTRAINT TABLE ***

	NODE	X1	X2	X3	X4	X5	X6
RESTRAINTS	29	1	1	1	1	1	1
RESTRAINTS	30	1	1	1	1	1	1
RESTRAINTS	31	1	1	1	1	1	1

This chart, identified as Figure 1, is the front view (y-z plane) of the CCR/clip assy math-model, showing the nodal locations.

CDC/MRI STARDYNE MATHEMATICAL MODEL FOR LAGEOS

1

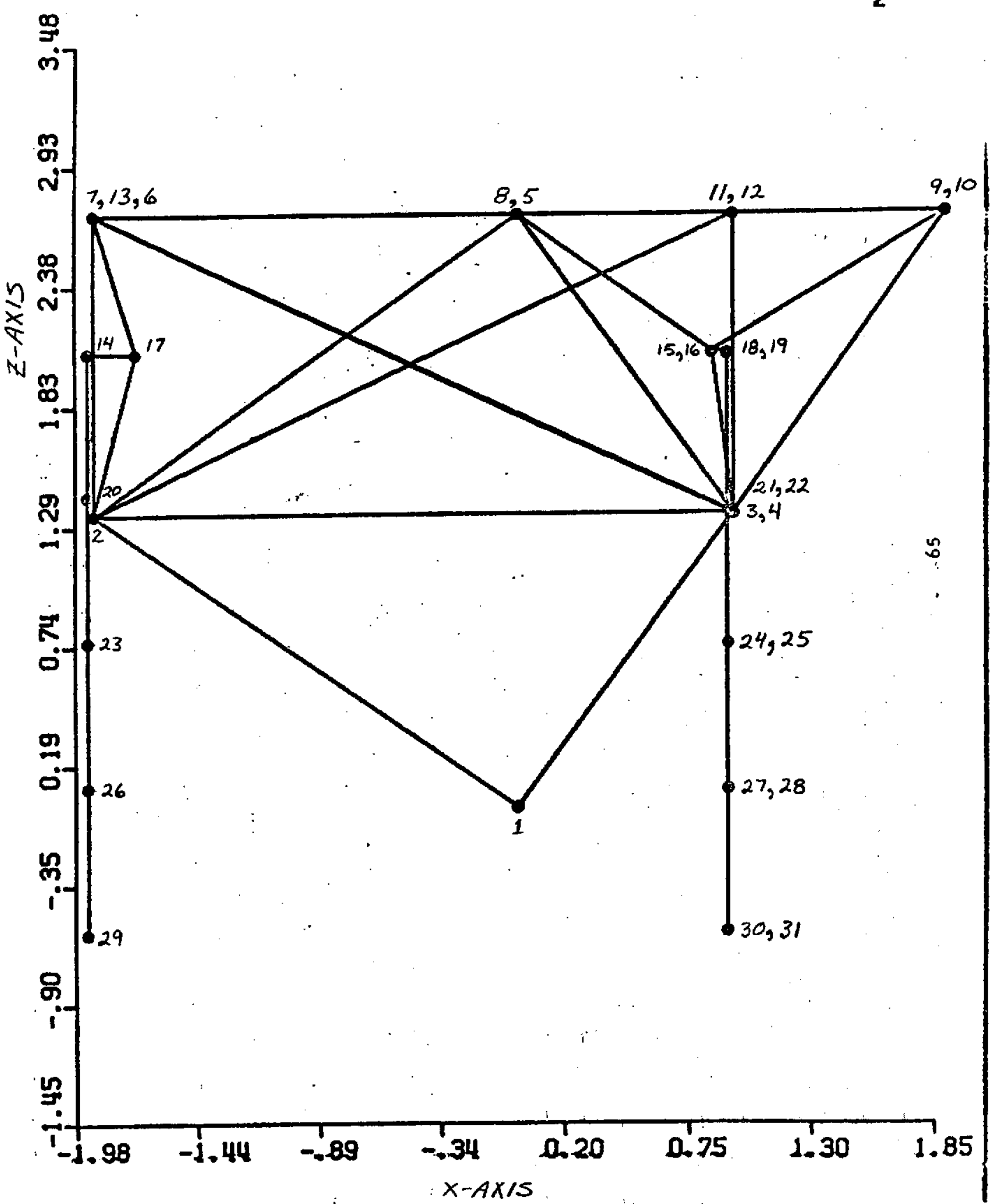


63

This chart, identified as Figure 2, is the side view (X-Z plane) of the CCR/clip assy math model, showing the nodal locations.

CDC/MRI STARDYNE MATHEMATICAL MODEL FOR LAGEOS

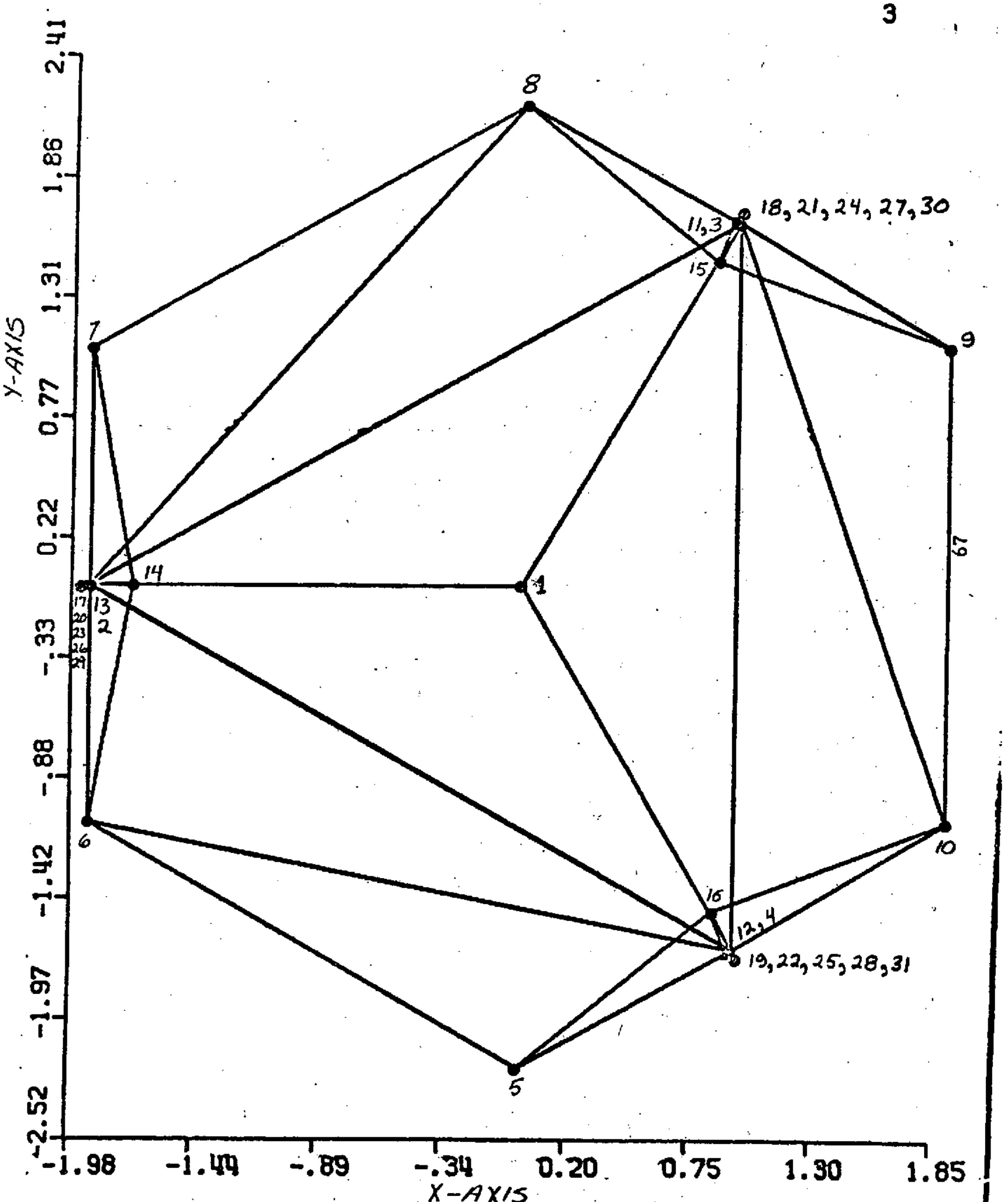
2



This chart, identified as Figure 3, is the top view (X-Y plane) of the CCR/clip assy math model, showing the nodal locations.

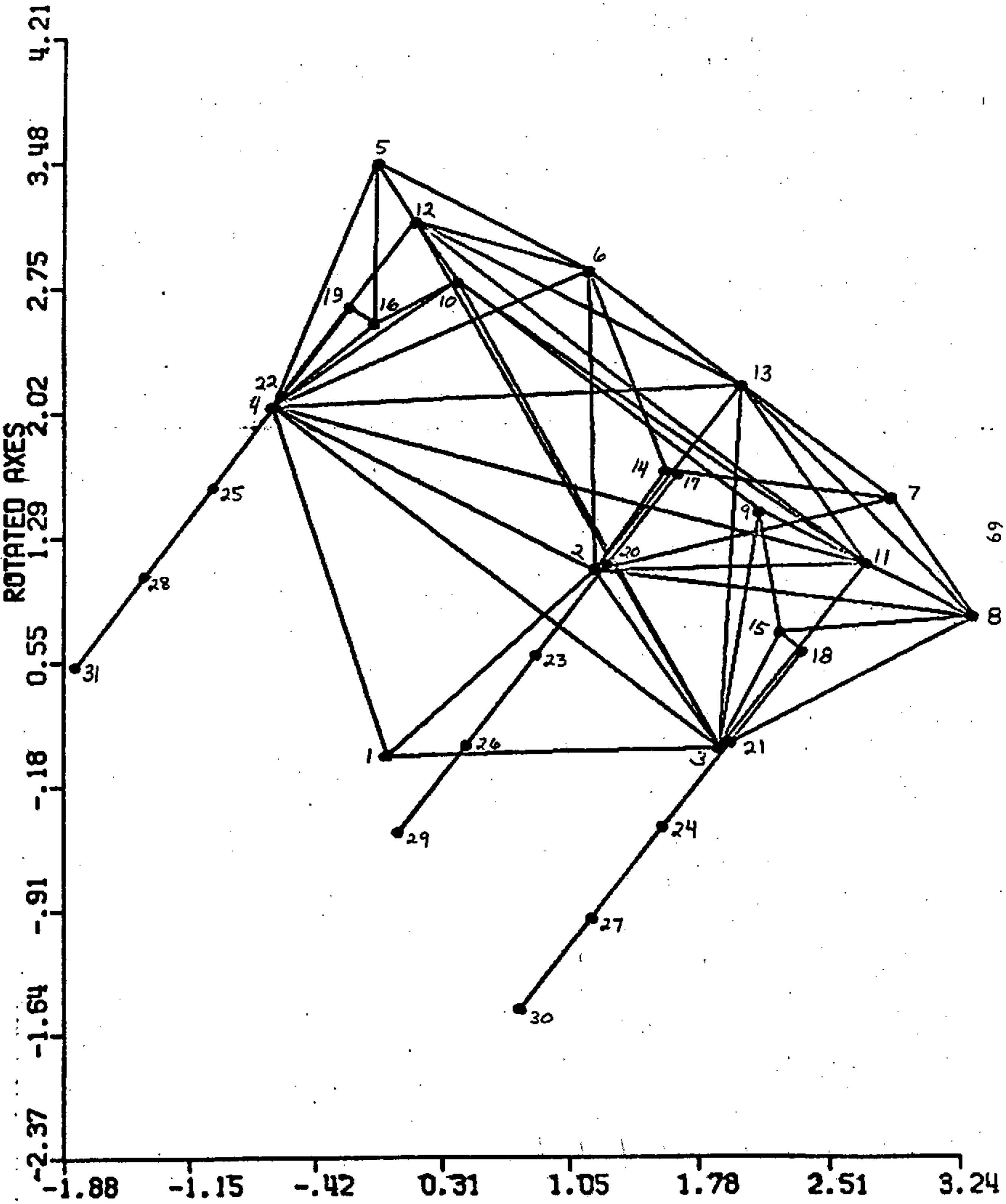
CDC/MRI STARDYNE MATEHMATICAL MODEL FOR LAGEOS

3



This chart, identified as Figure 4, is a rotated view of the CCR/clip assy math model, showing the nodal locations.

4


4.21
3.48
2.75
2.02
1.29
0.55
-.18
-.91
-1.64
-2.37
ROTATED AXES
-1.88
-1.15
-.42
0.31
1.05
1.78
2.51
3.24
5
12
6
19
16
10
22
4
13
14
17
7
9
2
20
11
8
15
18
25
28
31
23
1
26
3
21
29
24
27
30

This chart defines the specified (SOW and Study Plan Guidelines) sinusoidal and random vibration environment used as the base (nodes 29, 30, and 31) input levels to the math model for the dynamic analyses.

DYNAMIC ANALYSIS INPUTS

SINUSOIDAL VIBRATION INPUT (x, y, & z - Axes)

FREQ. RANGE (HZ)	LEVEL (g - peak)
5 - 16	2.3
16 - 22	6.8
22 - 200	2.3
200 - 2000	5.0

RANDOM VIBRATION INPUT (x, y, & z - Axes)

FREQ. RANGE (HZ)	LEVEL
20 - 300	+ 3 db/oct.
300 - 2000	0.05 g^2/HZ

This chart lists the sinusoidal vibration analysis results for the MSFC-designed hex-faced CCR/support clip assembly. Natural frequencies and maximum dynamic displacements are shown and compared with the allowable (cavity-limited) displacements. The CCR will exceed the allowable displacement in the X- and Y- directions. The clip displacements are acceptable. Also shown are the maximum stress level and the corresponding margin of safety, which predict structural failure. Failure stresses are predicted at the base of the clip and at the pins which support the CCR.

ANALYSIS RESULTS (0.0508 cm x 1.112 cm CLIP)

SINUSOIDAL RESPONSE - CCR

Input Axis	Natural Freq.	Response Axis	Maximum Displacement	Allowable Displacement
X	447 Hz	X	0.047 cm	0.029 cm
Y	447	Y	0.047	0.029
Z	365	Z	0.015	---

SINUSOIDAL RESPONSE - CLIP

Input Axis	Natural Freq.	Response Axis	Maximum Displacement	Allowable Displacement
X	331 Hz	X	0.072 cm	0.194 cm
Y	331	X-Y	0.063	0.194
Z	365	X	0.115	0.194

Maximum Stress : 71,210,000 gm/cm^2

Yield Stress : 9,140,000

Margin of Safety : Neg.

A-70

This chart lists the random vibration analysis results for the MSFC-designed hex-faced CCR/support clip assembly. Maximum dynamic displacements are given and compared with allowable (cavity-limited) displacements. The allowables are not exceeded. Also shown are the maximum stress level and the corresponding margin of safety, which are satisfactory.

ANALYSIS RESULTS (0.0508 cm x 1.112 cm)

RANDOM RESPONSE - CCR

Input Axis	Response Axis	R-M-S Displacement	Peak (3σ) Displacement	Allowable Displacement
X	X	0.0054 cm	0.016 cm	0.029 cm
Y	X - Y	0.0053	0.016	0.029 cm
Z	Z	0.0028	0.008	------

RANDOM RESPONSE - CLIP

Input Axis	Response Axis	R-M-S Displacement	Peak (3σ) Displacement	Allowable Displacement
X	X	0.0128 cm	0.038 cm	0.194 cm
Y	X - Y	0.0110	0.033	0.194
Z	X	0.0203	0.061	0.194

Maximum Stress (R-M-S)	:	506,000 gm/cm^2
Maximum Stress (peak - 3σ)	:	1,520,000
Yield Stress	:	9,140,000
Margin of Safety	:	+3.01

This chart shows the results for a modified clip design. To demonstrate the design concept feasibility, the clip was modified to increase its stiffness. The cross-sectional dimension were changed from 0.0508 cm x 1.112 cm to 0.127 cm x 1.6764 cm. The results of the sinusoidal analysis are shown here. The dynamic displacements have been reduced significantly, relative to the original design. Allowable displacements are more than twice maximum predicted displacements. Stresses were not computed.

I-73

ANALYSIS RESULTS (0. 127 cm x 1. 6764 cm)

SINUSOIDAL RESPONSE - CCR

Input Axis	Natural Freq.	Response Axis	Maximum Displacement	Allowable Displacement
X	1026 Hz	X	0. 00057 cm	0. 029 cm
Y	1026	Y	0. 00056	0. 029
Z	1063	Z	0. 00099	-----

SINUSOIDAL RESPONSE - CLIP

Input Axis	Natural Freq.	Response Axis	Maximum Displacement	Allowable Displacement
X	1026 Hz	X	0. 012 cm	0. 029 cm
Y	1026	X-Y	0. 011	0. 029
Z	1063	X	0. 008	0. 029

This final chart lists the significant conclusions derived from the analysis. The hex-faced clip mount design concept is feasible, but will require a stiffer support clip.

CONCLUSIONS

1) CLIP DESIGN CONCEPT IS FEASIBLE

2) 0.0508 cm (0.020 in.) CLIP IS STRUCTURALLY INADEQUATE.

3) 0.127 cm (0.050 in.) CLIP IS COMPATIBLE WITH PRESENT HOLE DIAMETER (4.445 cm).

Bendix Aerospace Systems Division

LAGEOS TEST PROGRAM STATUS

TEST PROGRAM SUMMARY

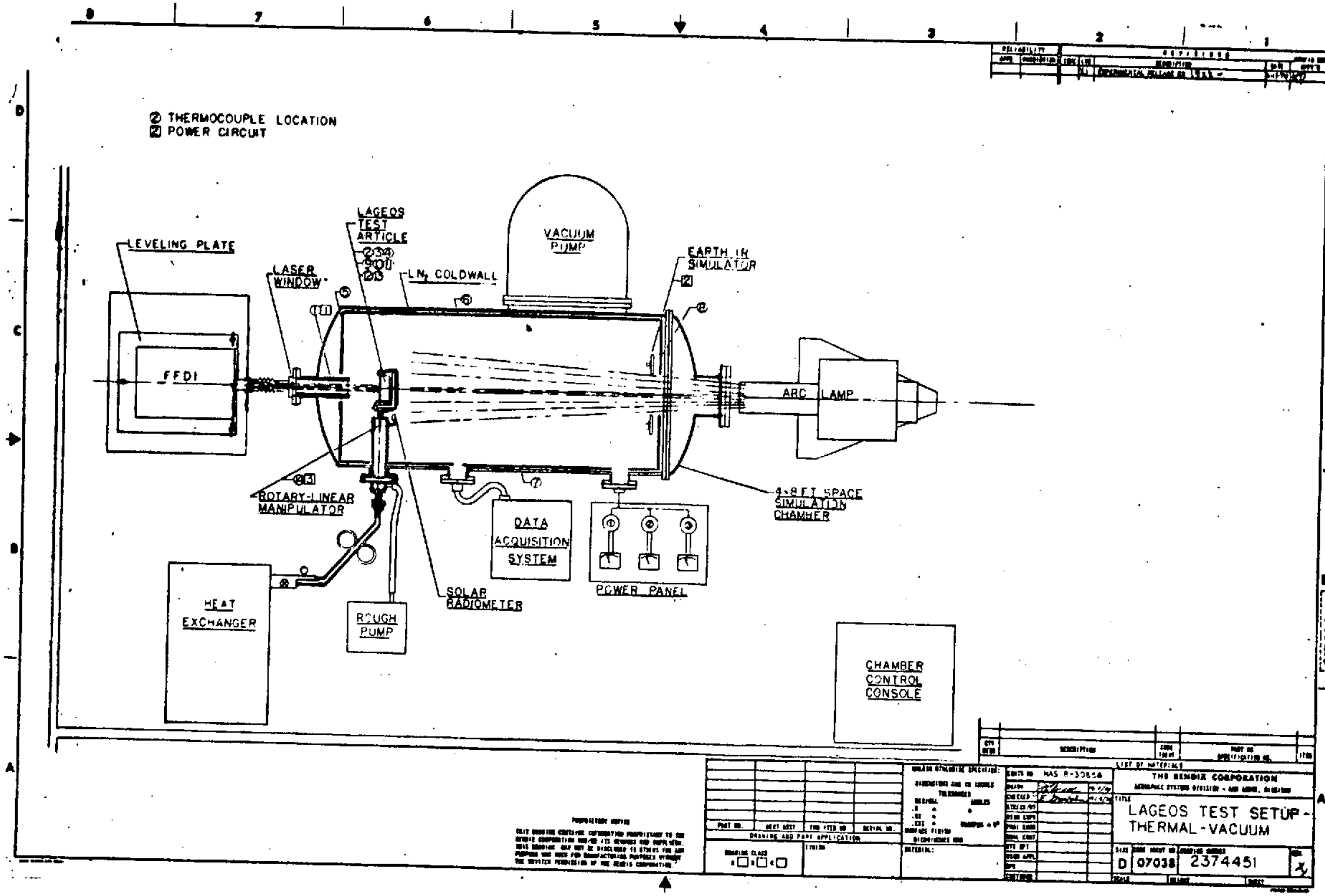
The current LAGEOS Phase B test program consists of four (4) basic test efforts. These tests and their objectives are defined in the Program Study Plan and are summarized to provide a basis for understanding the descriptions of the test articles, test equipment and test conditions which follow.

LAGEOS TEST PROGRAM SUMMARY

TESTS	OBJECTIVES
EARLY VIBRATION TESTS	- VERIFY DYNAMIC CHARACTERISTICS OF SELECTED MOUNT DESIGN FOR LAGEOS HEX-FACED RETROREFLECTOR AND LAGEOS WORST-CASE DYNAMIC ENVIRONMENTS
EARLY THERMAL/OPTICAL TESTS	- VERIFY TEST SET-UP - OBTAIN OPTICAL PERFORMANCE DATA FOR ALSEP AND GEOS-C RETROREFLECTORS - EARLY EVALUATION OF SELECTED THERMAL DESIGN PARAMETERS
FINAL THERMAL/OPTICAL TESTS	- OBTAIN LAGEOS RETROREFLECTOR FAR-FIELD PATTERNS AND PHOTOMETRIC MEASUREMENT OF RETURN BEAM FOR ISOTHERMAL AND SIMULATED ORBITAL THERMAL CONDITIONS (INCLUDING WORST-CASE) AND FOR VARIOUS LASER INCIDENCE ANGLES. TESTS ARE RUN BEFORE AND AFTER VIBRATION TESTS
FINAL VIBRATION TESTS	- EXPOSE THE FINAL TEST ARTICLE TO LAGEOS WORST-CASE DYNAMIC ENVIRONMENTS TO EVALUATE THE EFFECT ON THERMAL/OPTICAL PERFORMANCE.

OVERALL THERMAL/OPTICAL TEST ARRANGEMENT

The overall equipment arrangement, in and around the Bendix 4 x 8 vacuum chamber, is shown for the early and final thermal/optical tests. The test article is mounted in the thermal/optical test fixture, a rotary-linear manipulator. The test article will be rotated to face the solar simulator (arc lamp) and earth IR simulators to achieve the desired thermal conditions. A heat exchanger provides a temperature-controlled liquid to the test fixture for additional thermal control of the test article. The test article will then be rotated 180° to face the Far-Field Diffraction Instrument, which generates the laser beam and collects, displays, photographs and analyzes the diffraction pattern of the return beam. Thermocouples are mounted on the test article and at various places in the thermal/vacuum chamber. An optical (laser) window is mounted in the chamber, at the FFDI end, to permit entrance and exit of the laser beam with minimum beam degradation. Thermal control of this optical window is also provided to minimize thermal distortion of the window.


② THERMOCOUPLE LOCATION
[2] POWER CIRCUIT
LEVELING PLATE
FFDI
LASER WINDOW
LAGEOS TEST ARTICLE
LN2 COLDWALL
VACUUM PUMP
EARTH IR SIMULATOR
ARC LAMP
ROTARY-LINEAR MANIPULATOR
DATA ACQUISITION SYSTEM
POWER PANEL
4×8 FT SPACE SIMULATION CHAMBER
SOLAR RADIOMETER
HEAT EXCHANGER
ROUGH PUMP
CHAMBER CONTROL CONSOLE
THE BENDIX CORPORATION
LAGEOS TEST SETUP - THERMAL - VACUUM
D 07038 2374451

LAGEOS TEST ARTICLES - REQUIREMENTS

The requirements for the final test article were considered initially to establish the overall configuration of both the early and final test articles and the requirements for the thermal/optical test fixture design. These requirements are summarized in the chart.

The selection of the 0.25 inch cavity separation was made to ensure that the retroreflector/mount assembly would be exposed only to the specified satellite input environment and not be affected by conditions peculiar to the test article (i.e. not representative of the actual complete satellite structure which is expected to have a transmissibility of 1 to the retroreflector mount interfaces).

The requirements for the Early Test Article were then developed. The overall requirements are also summarized in the chart.

LAGEOS TEST ARTICLES - REQUIREMENTS

FINAL TEST ARTICLE

- PROVIDE MOUNTING FOR 6 LAGEOS RETROREFLECTORS (GEOS-C TYPE OR ALSEP-TYPE)
- 3 X 2 PATTERN (TEST FIXTURE DESIGN, SOLAR BEAM DIAM., THERMAL INSTR. REQTS.)
- CAVITY SEPARATION ≈ 0.25 IN. (DYNAMIC TEST, LASER BEAM REQTS)
- TIE-DOWNS FOR VIB. TEST & THERMAL/OPTICAL TEST
- MATERIAL: 6061-T6,OR EQUIV., ALUMINUM
- BACK SURFACE FLATNESS AND SURFACE FINISH FOR GOOD THERMAL CONTACT WITH THERMAL/OPTICAL FIXTURE.
- FRONT FACE SIZED BY ALSEP-TYPE LAGEOS RETROREFLECTOR
- HEIGHT SIZED BY GEOS-TYPE LAGEOS RETROREFLECTOR

EARLY TEST ARTICLE

- SAME SIZE AS FINAL TEST ARTICLE (TEST FIXTURE INTERFACES)
- SAME CAVITY LOCATIONS
- VIBRATION TEST: ONE CAVITY UTILIZED
- THERMAL/OPTICAL TEST: FOUR CAVITIES UTILIZED; VIBRATION CAVITY COVERED
- DETAIL REQUIREMENTS: SEE NEXT CHART

EARLY TEST ARTICLE - DETAIL REQUIREMENTS

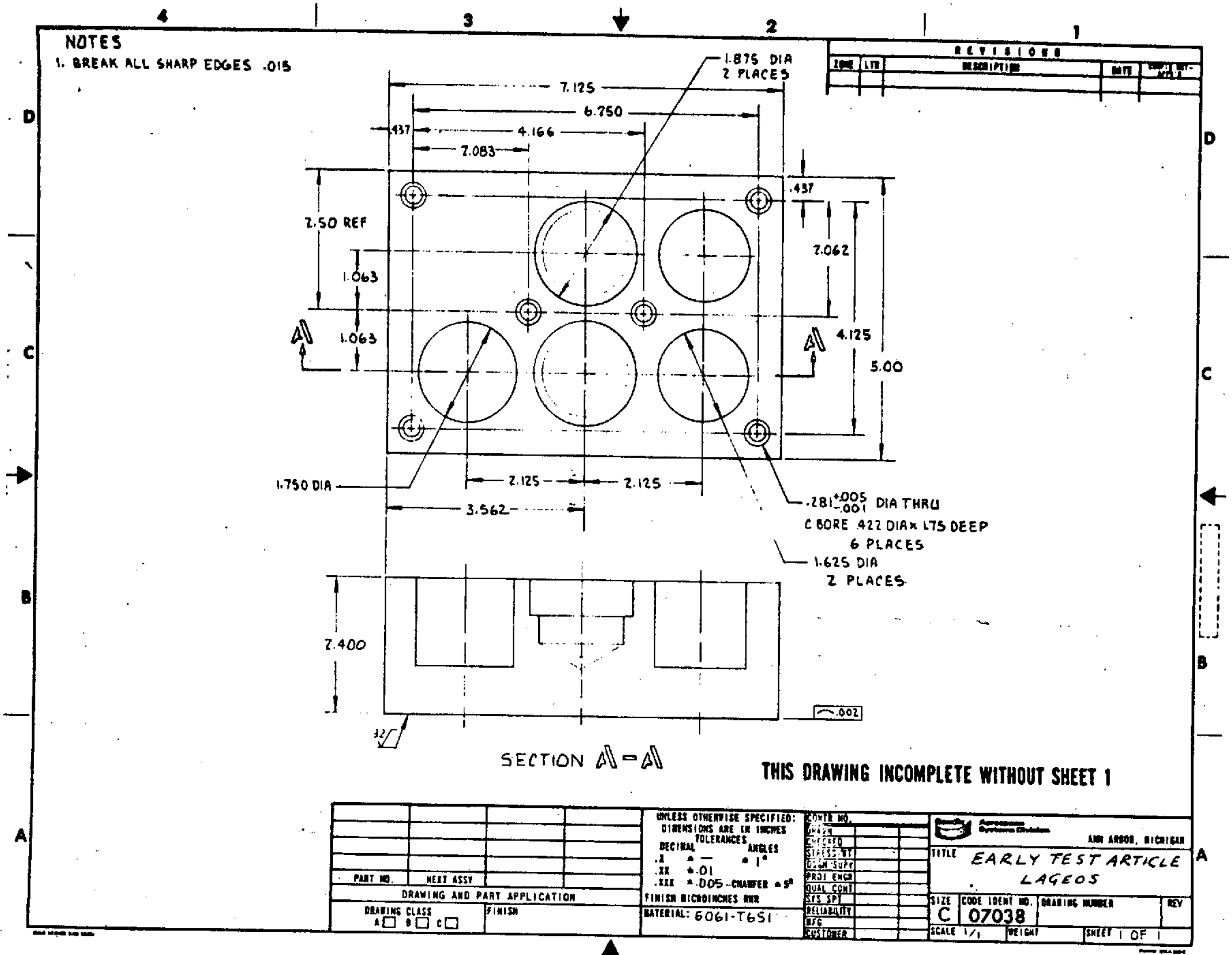
The detail requirements for the Early Test Articles are tabulated in the chart. It should be noted that during the Early Vibration Test, a simulated retroreflector will be mounted only in cavity A-1 and no retroreflectors will be in cavities B-1, B-2, C-1 and C-2. During the Early Thermal/Optical Test, the cavity A-1 will be capped over for thermal control reasons.

TABLE I

Early Test Article Applications	Early Vibration Test	Early Thermal/Optical Test				
Cavity Desig.	A-1	A-1	B-1	B-2	C-1	C-2
Retroreflector						
- Configuration	LAGEOS Hex-Faced	Capped Over	ALSEP	ALSEP	GEOS-C	GEOS-C
- Type	Aluminum Simulator w/Accel. Installed (3 Pico-Min Accel.)	N/A	Flight (GFE)	Dummy (GFE)	Flight (GFE)	Flight (GFE)
- Design	TBD (Based on MSFC Dwg 5OM 24466)	N/A	PE Dwg 100-2664 (Rev A)	PE Dwg 100-2664 (Rev A)	APL Dwg 7234-1076	APL Dwg 7234-1076
Mount						
- Configuration	LAGEOS Clip (Modified)	N/A	LAGEOS Rings (GFE)	LAGEOS Rings (GFE)	GEOS-C Clip (GFE)	GEOS-C Clip (GFE)
- Design	TBD (Based on Dynamic Analysis Results)	N/A	MSFC Dwg 5OM 24459	MSFC Dwg 5OM 24459	MSFC Dwg 5OM24467 (Rev--)	MSFC Dwg 5OM24467 (Rev--)
Cavity						
- Upper Dia	4.45 cm (1.75 in.)	N/A	4.76 cm (1.875 in.)	4.76 cm (1.875 in.)	4.13 cm (1.625 in.)	4.13 cm (1.625 in.)
- Upper Depth	As req'd for 1 mm Recess of Retroreflector Front Face	N/A	As req'd for 1 mm Recess Retroreflector Front Face			
- Lower Dia	N/A	N/A	3.94 cm (1.55 in.)	3.94 cm (1.55 in.)	N/A	N/A

EARLY TEST ARTICLE - CONFIGURATION

The configuration of the Early Test Article is shown in this chart, a partially-completed drawing for the test article panel. The lower left-hand cavity is A-1; the center two are B-1 and B-2 and the right-hand pair are C-1 and C-2. The test article panel is a 7.125 x 5 x 2.4-inch 6061-T6 aluminum block. The six holes provided for tie-down to the thermal/optical test fixture and the vibration test fixture are also shown.


NOTES
1. BREAK ALL SHARP EDGES .015
1.875 DIA
2 PLACES
7.125
6.750
.437
4.166
2.083
2.50 REF
1.063
1.063
.437
2.062
4.125
5.00
1.750 DIA
2.125
2.125
3.562
.281 +.005 -.001 DIA THRU
C BORE .422 DIA x 1.75 DEEP
6 PLACES
1.625 DIA
2 PLACES
2.400
.002
32
SECTION A-A
THIS DRAWING INCOMPLETE WITHOUT SHEET 1
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
PART NO.
NEXT ASSY
DRAWING AND PART APPLICATION
DRAWING CLASS A B C
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES
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ANGLES
.X ± —
± 1°
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FINISH MICROINCHES RMR
MATERIAL: 6061-T651
CONTR NO.
DRAWN
CHECKED
STRESS
PROJ ENGR
QUAL CONT
SYS SPT
RELIABILITY
MFG
CUSTOMER
ANN ARBOR, MICHIGAN
TITLE
EARLY TEST ARTICLE
LAGEOS
SIZE
C
CODE IDENT NO.
07038
DRAWING NUMBER
REV
SCALE 1/1
WEIGHT
SHEET 1 OF 1

FAR-FIELD DIFFRACTION INSTRUMENT (FFDI) REQUIREMENTS

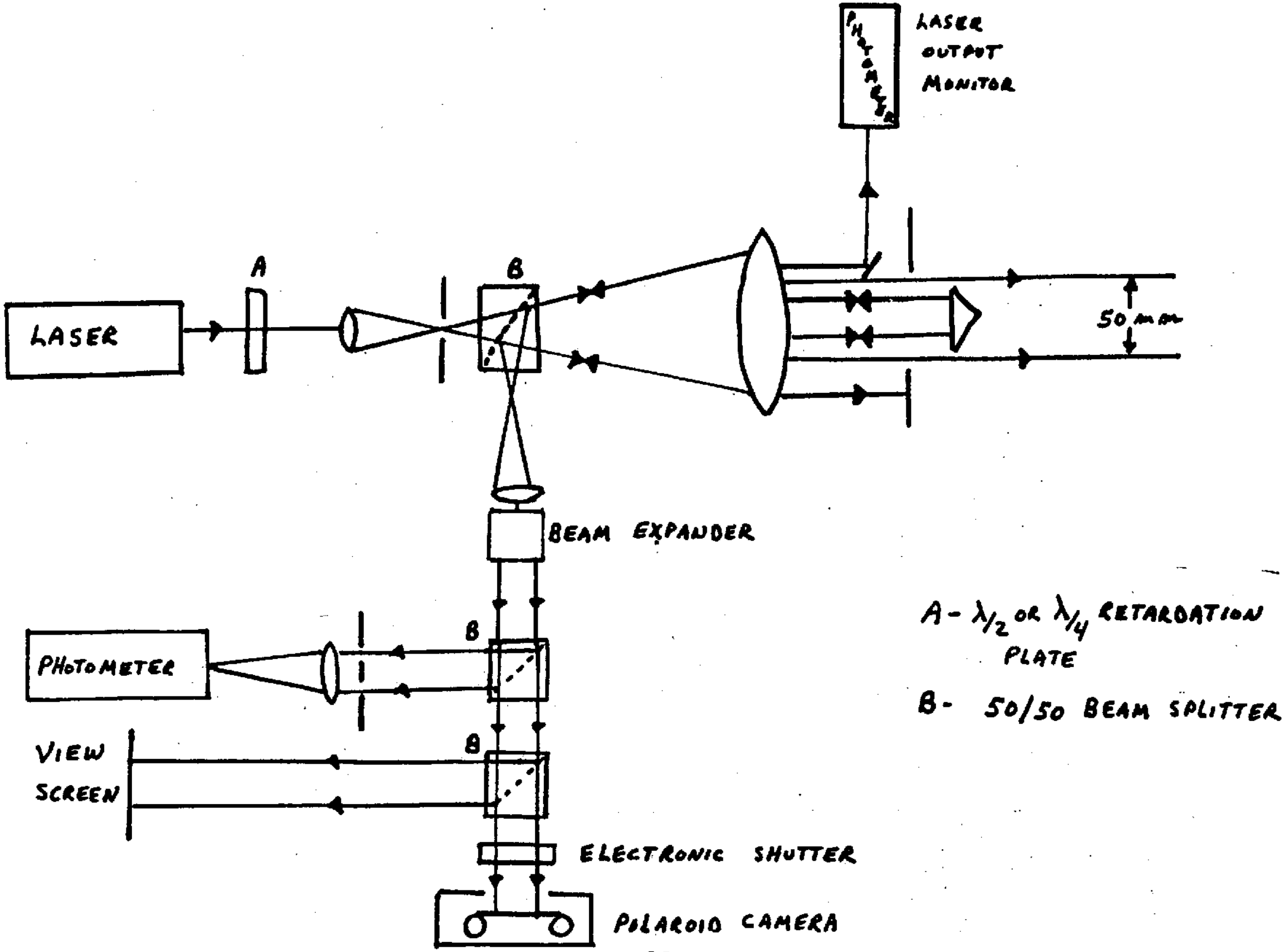
The requirements for the FFDI, the primary test instrumentation for the thermal/optical tests, are summarized. The measurement output of this instrument will be in three forms, as shown. The detail requirements are specified in a Bendix Requirements document which is the basis for the Zygo Corporation fabrication and test of the FFDI. The FFDI is being procured as Bendix capital equipment.

FAR-FIELD DIFFRACTION INSTRUMENT

The FFDI optical configuration is shown schematically in this chart. This configuration now eliminates the multiple-reflection interference effects of a linearly-polarized output and return beam, which was a problem in an earlier configuration. Either a linearly-polarized or a circularly-polarized beam may be selected, by insertion of the appropriate retardation plate.

The optical configuration has been breadboard tested at Zygo. Only the final retardation plates remain to be received at Zygo; an initial set was breadboard tested but was unacceptable for the final instrument.

FAR FIELD DIFFRACTION INSTRUMENT



TEST FIXTURE REQUIREMENTS

The various test fixtures are listed and their requirements are summarized. The designs for each will be described in later charts. The drawings for all, except the vibration test fixture, have been released for fabrication.

TEST FIXTURE REQUIREMENTS

THERMAL/OPTICAL TEST FIXTURE

- Support test article
- Test article positioning
- Thermal control for test article
- Test fixture thermal control & vacuum seal

OPTICAL WINDOW ASSEMBLY

- Support window at FFDI viewing port
- Limit window temperature gradients
- Vacuum seal

FFDI PLATFORM ASSEMBLY

- Support FFDI at chamber port
- Leveling & alignment with chamber & test article

VIBRATION TEST FIXTURE

- Use Thermal/Optical test article
- Transition plate to shaker tie-down
- Mounting for vibration control accelerometer

THERMAL/OPTICAL TEST FIXTURE

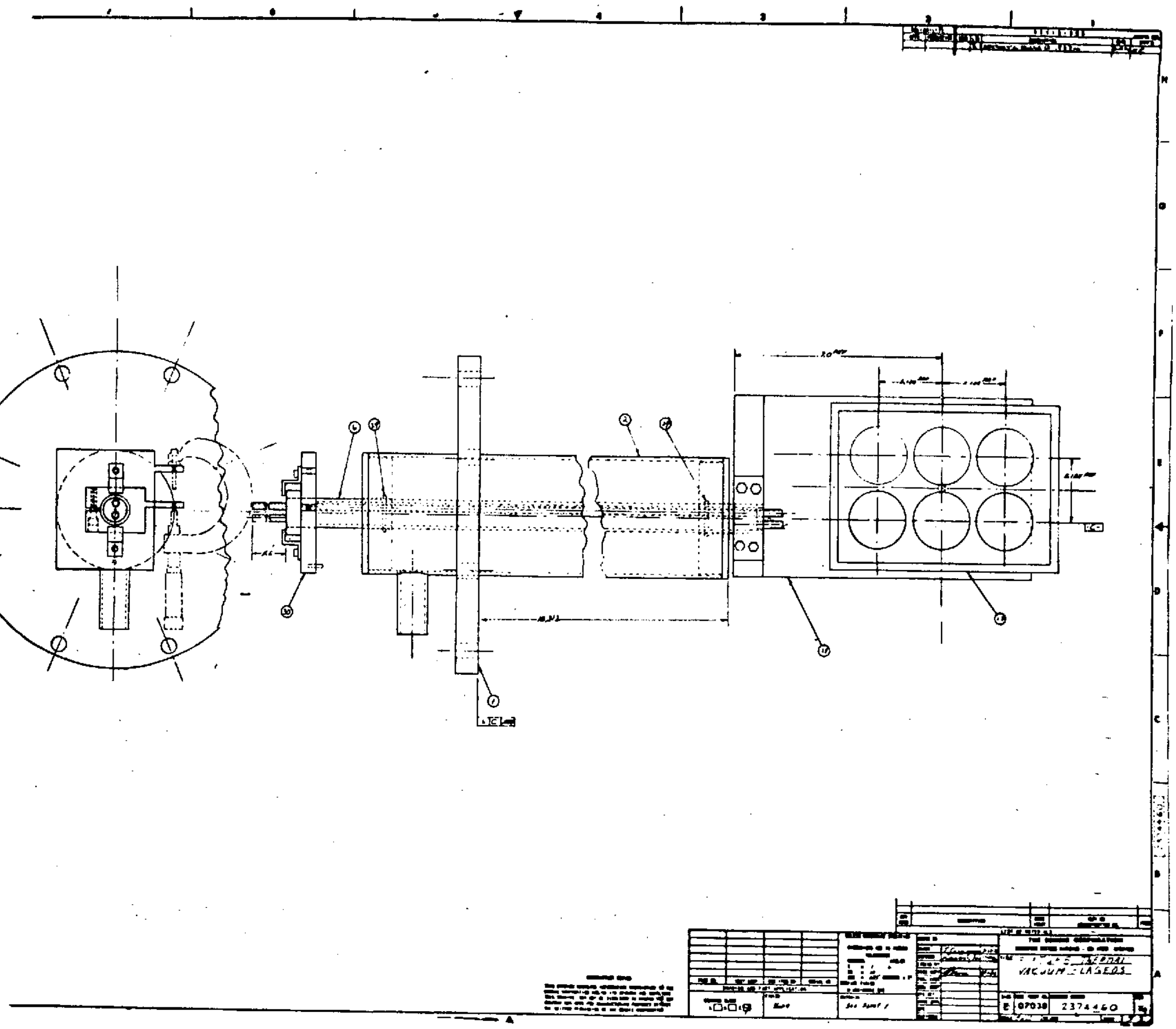
The detail requirements for the thermal/optical test fixture are summarized. The fixture provides support, orientation and thermal control for the test articles.

THERMAL/OPTICAL TEST FIXTURE

- SUPPORT TEST ARTICLE AT CHAMBER CENTER LINE
- LINEAR MANIPULATION PLACES SELECTED RETROREFLECTOR ON FFDI AXIS
- 180° ROTATION FOR VIEWING FFDI OR SOLAR RADIATION
- ROTARY INDEXING & VERNIER ORIENTATION OF SOLAR ANGLE AND FFDI READOUT
- TEST ARTICLE THERMAL CONTROL SHROUD WITH LIQUID LINES
- THERMAL CONTROL OF TEST FIXTURE
- SUPERINSULATION BLANKETING OF TEST ARTICLE AND TEST FIXTURE
- VACUUM SEAL AT CHAMBER PORT
- GUARD VACUUM FOR MANIPULATOR MECHANISM

THERMAL/OPTICAL TEST FIXTURE - DESIGN

The overall assembly design of the thermal/optical test fixture is shown in the chart, a reduction of one sheet of the drawings for the test fixture. The circular plate provides for attachment to the 4 x 8 chamber port and for sealing of the fixture to the port. The right end of the fixture shows the test article in place. The left end of the fixture is outside of the chamber and provides for manipulation control and access to the feed line tubing to the thermal control shroud at the test fixture location.



REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

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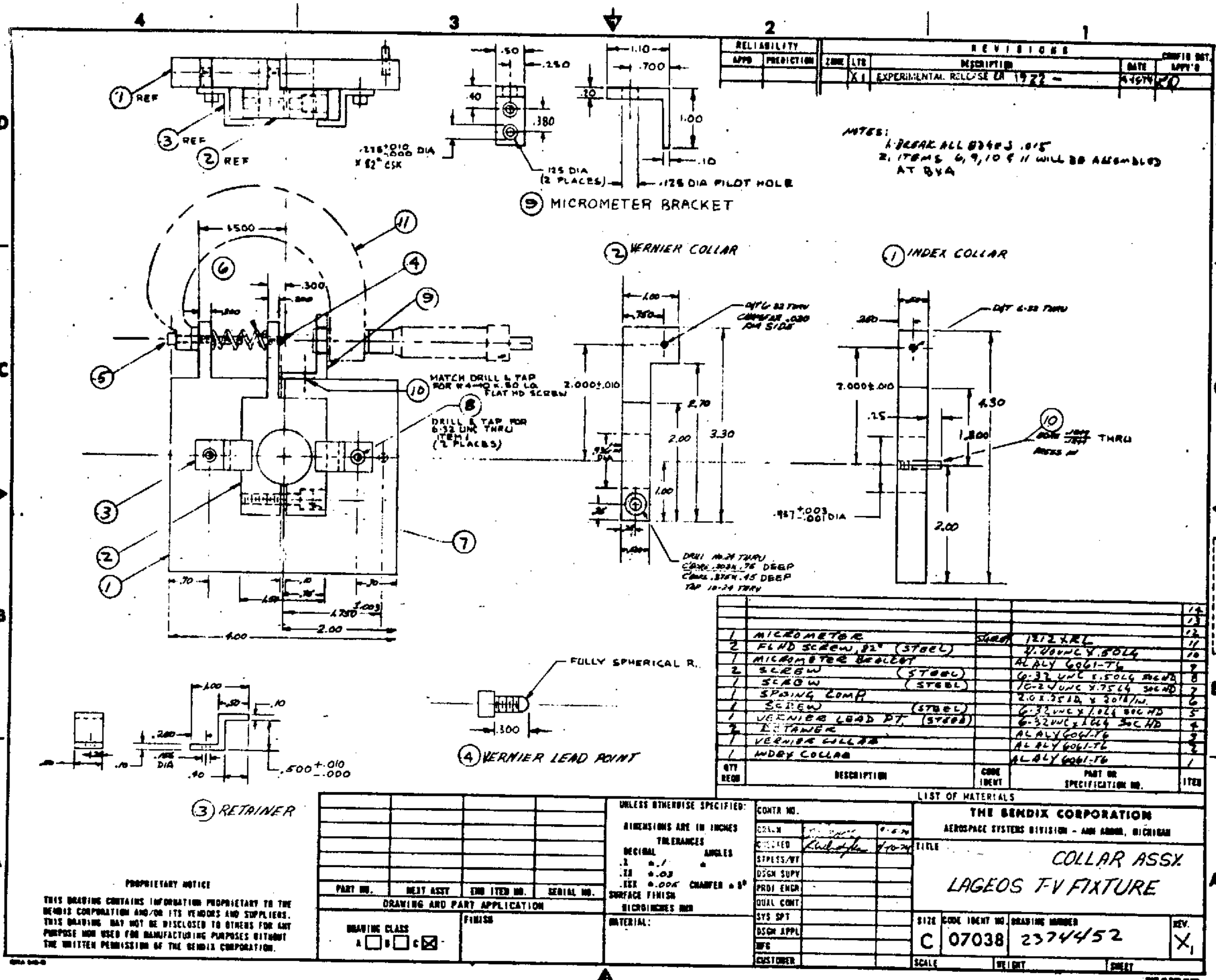
THERMAL/OPTICAL TEST FIXTURE - ORIENTATION ADJUSTMENT DESIGN

The means for fine adjustment of the test fixture, and the test article, is shown in the chart. A reduction of the drawing which describes the hardware provided for this micrometer adjustment is shown. Gross orientation control is provided by 10° incremental settings. The micrometer adjustment hardware provides the means for fine adjustment between these 10° increments.



QTY REQD	DESCRIPTION	CODE IDENT	PART OR SPECIFICATION NO.	ITEM
				14
				13
				12
1	MICROMETER	STARRETT	1212 XRL	11
2	FLHD SCREW, 82° (STEEL)		4-40 UNC X .50 LG	10
1	MICROMETER BRACKET		AL ALY 6061-T6	9
2	SCREW (STEEL)		6-32 UNC X .50 LG SOC HD	8
1	SCREW (STEEL)		10-24 UNC X .75 LG SOC HD	7
1	SPRING COMP		2.0 X .25 I.D. X 20 LB/IN.	6
1	SCREW (STEEL)		6-32 UNC X 1.0 LG SOC HD	5
1	VERNIER LEAD PT. (STEEL)		6-32 UNC X 1 LG SOC HD	4
2	RETAINER		AL ALY 6061-T6	3
1	VERNIER COLLAR		AL ALY 6061-T6	2
1	INDEX COLLAR		AL ALY 6061-T6	1

LIST OF MATERIALS

PROPRIETARY NOTICE

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UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES

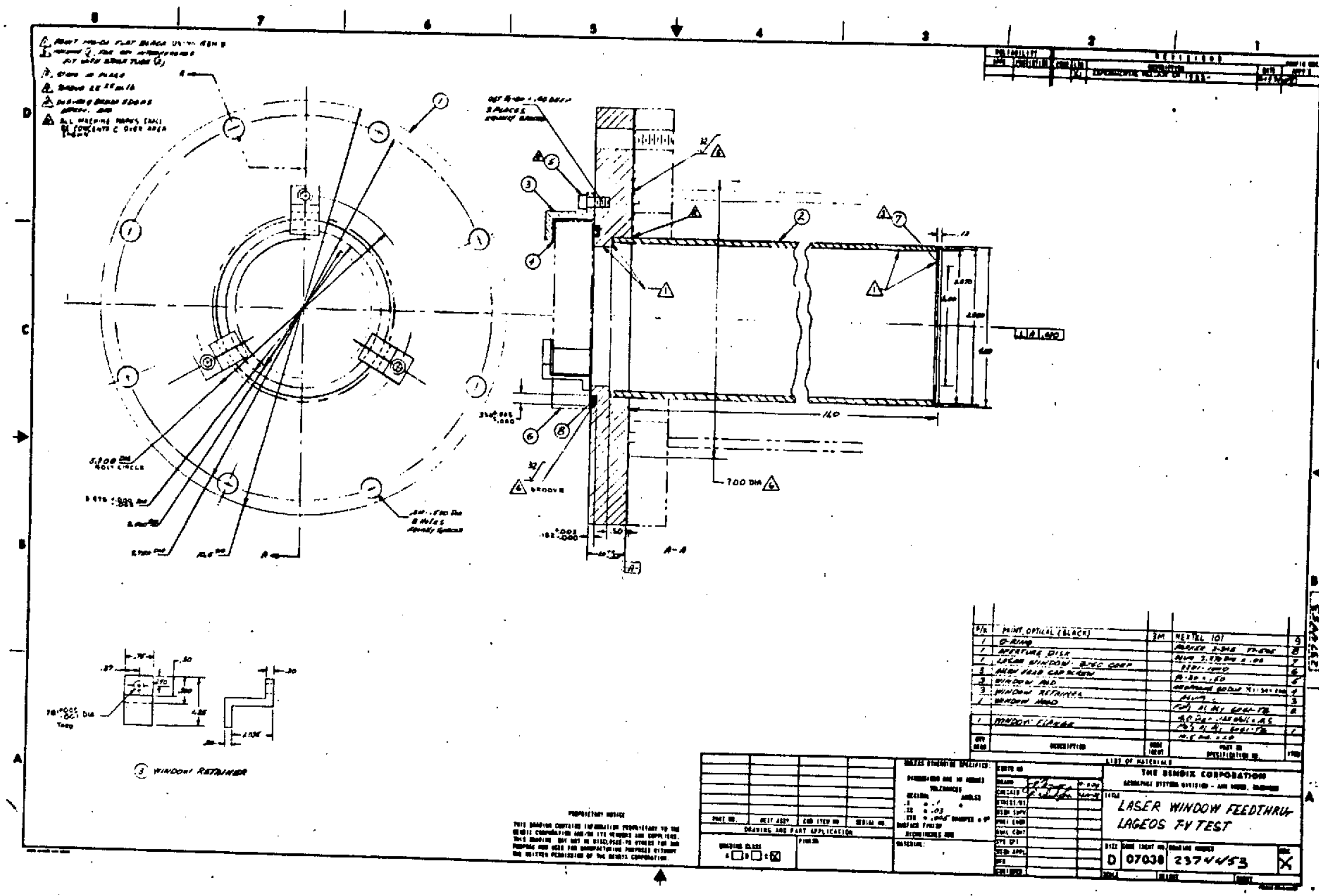
THE BENDIX CORPORATION
AEROSPACE SYSTEMS DIVISION - ANN ARBOR, MICHIGAN

TITLE: COLLAR ASSY. LAGEOS T-V FIXTURE

SIZE C — CODE IDENT NO. 07038 — DRAWING NUMBER 2374452 — REV. X1

OPTICAL WINDOW ASSEMBLY

The drawing for fabrication and assembly of the optical window assembly is shown in this chart. The assembly supports the optical (laser) window and provides the seal at the window. A thermal control hood is provided on the assembly to shield the optical window from the cold wall and maintain the window in an isothermal condition. The hood will include a heater and will be covered by multilayer insulation. The entire assembly will be mounted and sealed at the existing port in the end of the 4 x 8 chamber, opposite the chamber door.



LIST OF MATERIALS
PAINT OPTICAL (BLACK)
3M
NEXTEL 101
O-RING
APERTURE DISK
LASER WINDOW
WINDOW PAD
WINDOW RETAINER
WINDOW HEAD
WINDOW CARRIER
DESCRIPTION
THE BENDIX CORPORATION
LASER WINDOW FEEDTHRU
LAGEOS T-V TEST
D
07038
237VV53
A-A
GROOVE
WINDOW RETAINER
PROPRIETARY NOTICE

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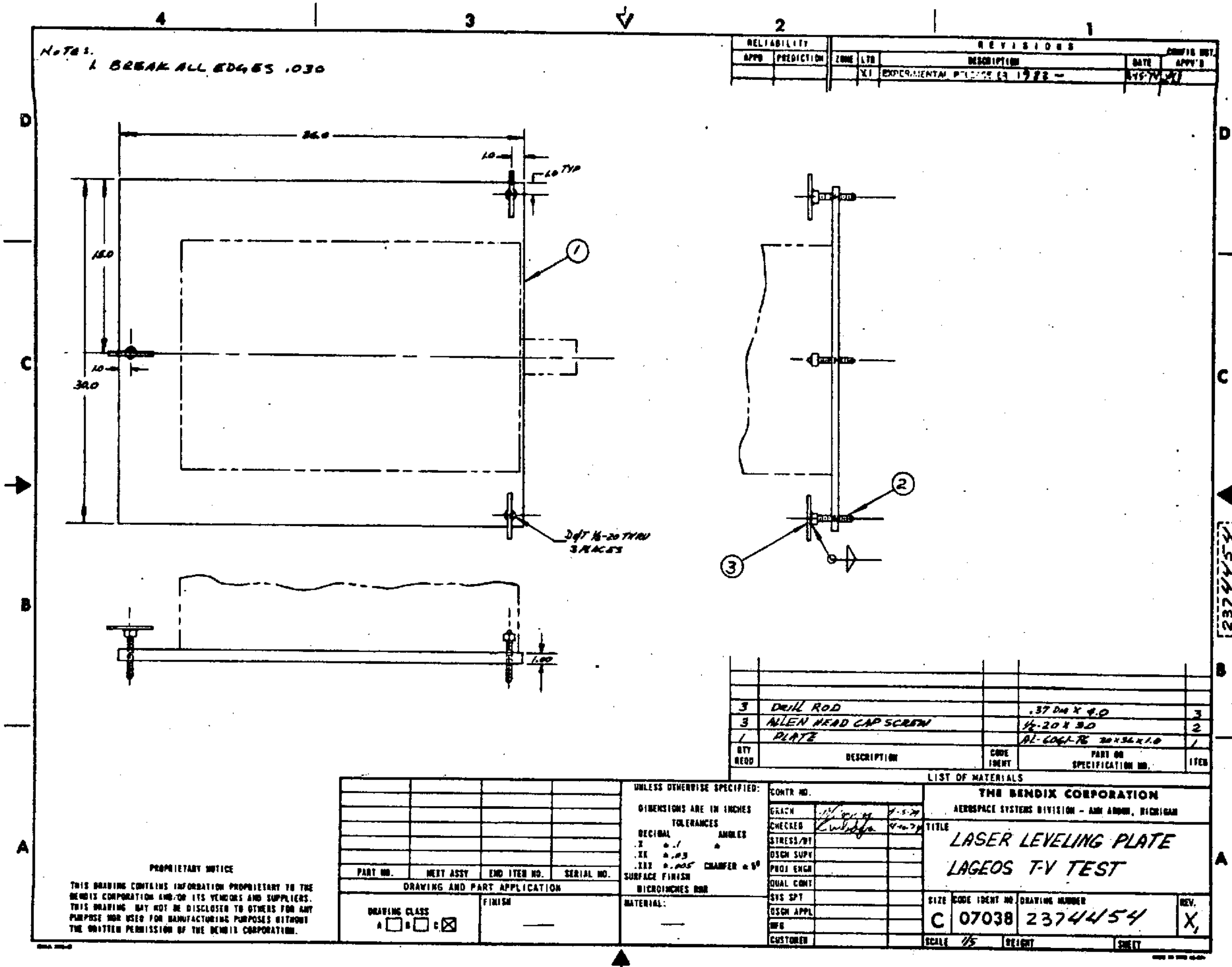
FFDI PLATFORM ASSEMBLY

The FFDI will be mounted on a platform assembly to provide a means for aligining the FFDI laser beam with the test article target retroreflector on the chamber center-line. Three screws are provided for adjustment purposes. The drawing for this assembly is shown in the chart.


NOTES:
1. BREAK ALL EDGES .030
REVISIONS
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36.0
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1.0 TYP
18.0
30.0
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D&T 1/4-20 THRU 3 PLACES
1.00
1
2
3
3 | DRILL ROD | .37 DIA X 4.0 | 3
3 | ALLEN HEAD CAP SCREW | 1/4-20 X 3.0 | 2
1 | PLATE | AL-6061-T6 30 X 36 X 1.0 | 1
QTY REQD | DESCRIPTION | CODE IDENT | PART OR SPECIFICATION NO. | ITEM
LIST OF MATERIALS
THE BENDIX CORPORATION
AEROSPACE SYSTEMS DIVISION - ANN ARBOR, MICHIGAN
TITLE
LASER LEVELING PLATE
LAGEOS T-V TEST
SIZE C
CODE IDENT NO. 07038
DRAWING NUMBER 2374454
REV. X1
SCALE 1/5
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES
DECIMAL .X ±.1 .XX ±.03 .XXX ±.005
CHAMFER ± 5°
SURFACE FINISH
MICROINCHES RMS
MATERIAL:
PART NO. | NEXT ASSY | END ITEM NO. | SERIAL NO.
DRAWING AND PART APPLICATION
DRAWING CLASS A B C
FINISH
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LAGEOS VIBRATION TEST FIXTURE

The chart summarizes the requirements for the design of the vibration test fixture. The fixture provides a transition between the test article and the Bendix vibration test system. Detail design and generation of the drawing for this fixture has not yet begun.

LAGEOS VIBRATION TEST FIXTURE

MATERIAL: ALUMINUM ALLOY (AVAILABLE STOCK)

SIZE: APPROX. 7 X 10 X 1 1/2

THREADED HOLES: TIE-DOWN OF TEST ARTICLE TO TEST FIXTURE; PATTERN AS DEFINED IN TEST ARTICLE DWG.

COUNTER-BORED THRU-HOLES: TIE-DOWN OF TEST FIXTURE TO SHAKER HEAD OR SLIP PLATE

PATTERN TO BE SELECTED FROM THREADED HOLES ON SHAKER HEAD OR SLIP PLATE AND TO BE CLEAR OF TEST ARTICLE TIE DOWN HOLES.

TEST EQUIPMENT AND EXPENDABLES

The chart summarizes the test equipment and expendable items required for the LAGEOS test program. The three test fixtures, previously described, are also listed. The due dates shown are the present schedule dates; the fabrication of the piece parts for these fixtures have had to be off-loaded to outside shops, because of the current work load in the Bendix manufacturing facility, and confirmed dates are not yet available.

All test equipment and expendables are presently available at the Plant 2 facility, with the exception of the special fine-wire thermocouples required for instrumentation of the test article, which are being procured.

TEST EQUIPMENT AND EXPENDABLES

TEST FIXTURES

• Thermal/Optical Test Fixture	Due in 4/26/74
• Window Feed-thru Assembly	Due in 4/26/74
• FFDI Leveling Plate	Due in 4/26/74

TEST EQUIPMENT

• T/V Chamber (4x8)	Available *
• Solar Simulator (2)	Available
• Radiometer	Available
• Heat Exchanger	Available*
• Data Acquisition System	Available*
• Roughing Pump	Available
• Power Control & Metering	Available
• Optical Alignment Instrumentation	Available*
• FFDI Support Table	Available
• Earth IR Simulator	Available
• Vibration Test System	Available*
• Polaroid Camera	Available*
• Vibration Instrumentation	Available*

EXPENDABLES

• Test article thermocouples	Due in 4/30/74
• Cryowall & fixture thermocouples	In Stock
• Liquid Nitrogen	In Stock
• Carbon Rods	In Stock
• Magnetic tape	In Stock
• Polaroid film	In Stock

*By Schedule

LAGEOS TEST PROGRAM - WORST CASE DYNAMIC ENVIRONMENT

The vibration environment presently defined for the LAGEOS satellite and planned to be imposed on the Test Articles is shown in the chart. It can be seen that there are two "open" items (TBD) in the chart for which inputs are required from MSFC. These levels on those presently defined in the contract SOW and the Study Plan guidelines.

LAGEOS TEST PROGRAM
WORST-CASE DYNAMIC ENVIRONMENT

SINUSOIDAL VIBRATION (2 OCT/MIN) (THREE AXES - ONE SWEEP PER AXIS)

5-16 HZ	2.3 g-PEAK	
16-22	6.8	
22-100	2.3	
100-200	TBD	EQUIVALENT SHOCK ENVIRONMENT
200-2000	5.0	EQUIVALENT SHOCK ENVIRONMENT

RANDOM VIBRATION (DURATION: TBD) (THREE AXES)

20-300 HZ	+3 dB/OCT.	9.8 GRMS
300-2000 HZ	0.05 G^2/HZ	9.8 GRMS

EARLY THERMAL/OPTICAL TEST CONDITIONS

The test conditions currently defined in the Test Plan for the early thermal/optical tests are shown in the chart. Optical performance will be measured on two different retroreflector configurations, each in the orientation shown and at the laser field angles indicated. These early tests are intended to provide a test set-up checkout, obtain some performance data on the ALSEP and EOS-C retroreflectors to provide an early indication of the behavior of the retroreflectors under these conditions and to permit evaluation of the basic thermal conditions selected.

These are tentative selections and will be under review at Bendix prior to the next update of the Test Plan. MSFC comments and suggestions are desired prior to final selection for the Test Plan update.

Early Thermal/Optical Test Conditions

Test	Test Type	Retroreflector Orientation		Pressure (Torr)	Test Article (Core) Temp. (°C)	Cold wall Temp. (°C)	Solar Angle	Laser Field Angles	Laser Polarization
		Parallel to Edge	Perpendicular to Edge						
1	Isothermal/Ambient	G	A	Ambient	Ambient	Ambient	N/A	A: -16° -10° 0° +30° +45° G: -20° -10° 0°	Linear in plane of laser field angles.
2	Isothermal/Vacuum	G	A	1×10^{-6}	Ambient	Ambient	N/A	Same	Same
3	Thermal/Vacuum	G	A	1×10^{-6}	TBD (-30 $\pm$ 15) Est.	-185	1 Sun	Same	Same

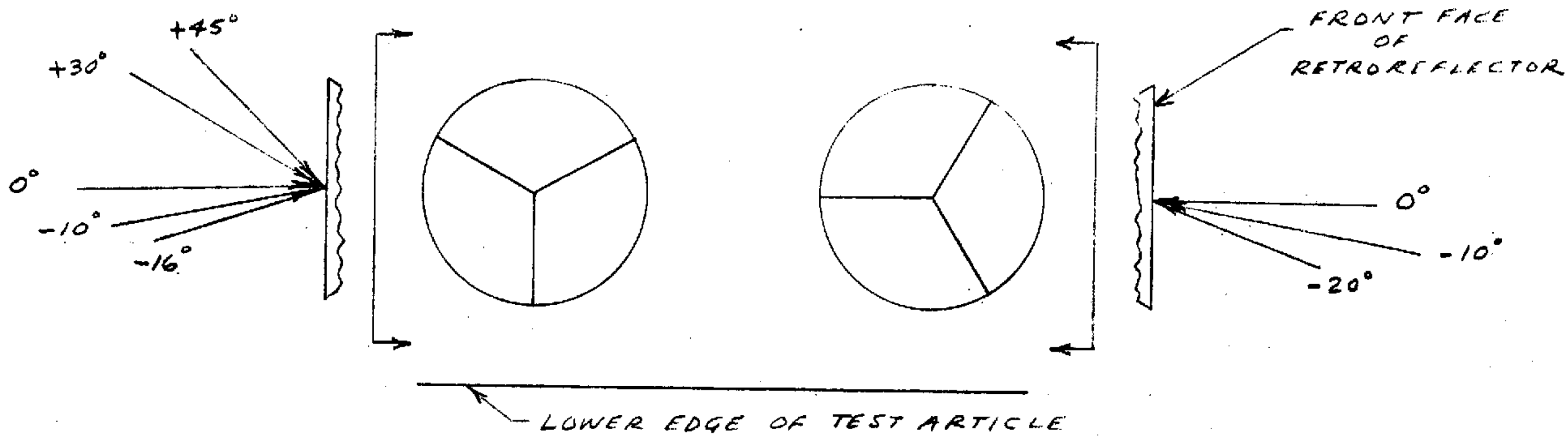
G = GEOS - C Retroreflector

A = ALSEP Retroreflectors

LASER FIELD ANGLES - THERMAL/OPTICAL TESTS

This chart defines the laser field angles shown in the previous chart for the early test program. It also applies to the following chart for the Final Test Program. It is believed the angles selected provide the optimum amount of data and will permit generation of performance curves as a function of laser field angle. Three of the angles shown (-10, 0, -30) correspond to those for which optical performance is being generated analytically, at Itek.

LASER FIELD ANGLES - THERMAL/OPTICAL TESTS



FINAL THERMAL/OPTICAL TEST CONDITIONS

This chart shows the present plan for test conditions in the Final Thermal/ Optical Tests. It has been increased in scope from that originally proposed by Bendix. The number of laser field angles for which data is being obtained has been increased from 6 to 8. As shown in the previous chart these are selected to provide more data points for a more accurate representation of performance versus laser field angle. Tentative test article temperature is shown; the final level will be obtained from the thermal analysis task and is dependent on the satellite coating characteristics selected. The range of solar angles selected should provide sufficient data on the effects of both retroreflected and "break-through" solar heating.

As in the previous chart, these are tentative selections and MSFC comments and suggestions are solicited to supplement Bendix review inputs. The final selections will be incorporated in the final Test Plan update.

FINAL THERMAL/OPTICAL TEST CONDITIONS

Test	Description	Retroreflector Orientation		Vacuum Chamber Pressure (Torr)	Test Article Temperature (°C)	Chamber Cold wall Temp. (°C)	Solar Angle	Total Laser *** Field Angles Per Test
		Parallel to Edge	Perpendicular to Edge					
1	Isothermal/Ambient	A, B*	A, B	Ambient	Ambient	Ambient	N/A	16**
2	Isothermal/Vacuum	A	B	1×10^{-6}	Ambient	Ambient	N/A	8
3	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	1 sun - 45°	8
4	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	1 sun -20°	8
5	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	1 sun Normal	8
6	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	1 sun + 30°	8
7	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	1 sun +60°	8
8	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	Simulated Earth IR	8
9	Thermal/Vacuum	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	No Sun	8
Vibration Test								
10	Isothermal/Vacuum	A	B	1×10^{-6}	Ambient	Ambient	N/A	8
11	Lowest Optical Return Thermal Test	A	B	1×10^{-6}	TBD ($-30 \pm 15^\circ C$)	-185	TBD	8

* A and B correspond to two reflectors and their orientation in the test article.
** Parallel to Edge: - 20°, -10°, 0; Perpendicular to Edge: -16°, -10°, 0, +30°, +45°.
*** Laser Polarization: Linear, Orientation TBD.

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Internal Memorandum

APPENDIX B

Bendix Aerospace Systems Division

Ann Arbor, Michigan

Date April 30, 1974 Letter No. LAGEOS-18

To Attendees

From J. Brueger, Bendix LAGEOS Program Manager

Subject Bendix LAGEOS Program Review, Minutes

Reference: (a) Contract NAS 8-30658
(b) First Program Review - Bendix LAGEOS Phase B Program LAGEOS - 17, on 17 and 18 April 1974

1. The subject meeting was conducted at Bendix Aerospace Systems Division, Ann Arbor, Michigan on 17-18 April 1974. The attendees are listed on the attached Table 1. Copies of the vu-graphs in the Bendix presentation and the MSFC presentation were provided as handouts to all attendees. As required by the program contract (Reference a), the Bendix data is being submitted separately as reference (b). The MSFC handouts are included herein, as Attachment A.

2. The Program Review agenda reflects the scope of subject matter covered in the presentations and technical discussions. The agenda is shown in Table 2. On the basis of the data presented and the discussions related to the data, a number of agreements were reached during the meeting. In addition, action items for MSFC, SAO and Bendix were identified during the discussions.

3. The decisions made during the meeting discussion are summarized as follows:

3.1 LAGEOS Retroreflector Configuration

Decision: The circular-faced tab-mounted (ALSEP-type) retroreflector design was selected for the remaining thermal/optical and dynamic analyses and tests in the Bendix LAGEOS Phase B program.

Discussion: After presentation of the Bendix and MSFC results of analysis and test efforts (see reference (b) and Appendix A), the question of retroreflector configuration was discussed for some time. During the discussions, SAO representatives indicated that SAO satellite performance analysis had thus far only considered the circular configuration and that the hex-configuration mounted in circular cavities presented analytical modeling complexities, especially for off-axis viewing. In addition, SAO representative, T. Hoffman, emphasized that the circular-faced configuration had the advantage of considerable analytical, test and flight experience in its favor, which must be a consideration in the selection decision. SAO representative, D. Arnold, indicated that retroreflector-to-retroreflector consistency, in the return beam performance of the retroreflectors, was desirable for return data interpretation. Also, he indicated that a minor reduction in the number of retroreflectors on the satellite, such as may be realized by the effect of increased cavity diameter for the circular-faced configuration, and minor reduction in retroreflector face-area are acceptable. The SAO representatives recommended selection of the ALSEP-type configuration.

A list of advantages and disadvantages for each of the two configurations, with regard to several major areas of consideration, was generated from the discussion inputs. This list is shown in Table 3. The conclusions reached from this comparison, as summarized by Mr. D. Bowden MSFC, was that neither configuration had significant advantages or disadvantages sufficient to eliminate one, or the other, from further consideration.

At the start of the second day of the review, J. Brueger, Bendix, presented the results and recommendations of a Bendix evaluation of the two configurations, made after adjournment of the first day's session. Since neither configuration could be clearly eliminated on the basis of analysis and test data developed to date, the goal of the evaluation was to look for "shades of grey" which would provide the basis for a selection. Bendix recommended selection of the circular-faced (ALSEP-type) configuration on the basis of the evaluation results summarized in Table 4. Mr. D. Bowden, MSFC, stated that MSFC concurred with the recommendation.

3.2 LAGEOS Phase B Thermal/Optical and Vibration Tests

Decision: Delete the early thermal/optical and vibration tests, including the early test article, and increase the scope of the final thermal/optical tests to obtain thermal/optical performance for the six (6) LAGEOS retroreflectors to be fabricated for Phase B.

Discussion: The preceding decision(in 3.1), which selected the circular-faced retroreflector for the LAGEOS design to be analyzed and tested in the remainder of the program, reduces the value of conducting early vibration tests on the hex-faced retroreflector. Also, the thermal/optical tests planned for the early test article, in which data was to be obtained for the ALSEP and the GEOS-C retroreflectors, would provide data that is no longer of interest. The effort planned for the fabrication of the early test article and the testing itself would be more effectively applied in the program by extending the final thermal/optical tests to obtain thermal/optical performance data for all six (6) available LAGEOS circular-faced retroreflectors. Based on no design optimization being required for the MSFC-designed mounting rings of the circular-faced retroreflector and earlier availability of the LAGEOS retroreflector, it is expected that the final thermal/optical tests could be started earlier than presently planned and be completed within the present schedule.

4. The Action Items resulting from the review are as follows:

4.1 Thermal Analysis: Include an evaluation of the effects of recessing the retroreflector (circular-faced on the Kel-F ring mount), in the remaining parametric thermal analysis.

Action: Bendix

4.2 Mounting Ring Design: Validate the design to ensure it integrates with the existing circular-faced retroreflector design/hardware. Update the design to include a retainer ring, above the upper Kel-F ring, for thermal control purposes.

Action: MSFC

4.3 Satellite Design: Update the satellite design to incorporate the circular-faced retroreflector and mount designs.

Action: MSFC

4.4 Dielectric Beam-Splitter Effects: Verify that a dielectric beam splitter in the optical test set-up has no unacceptable effect on the far-field diffraction pattern.

Action: MSFC

4.5 Study Plan and Test Plan: Update, to reflect decisions on the selection of the circular-faced retroreflector and the deletion of the Early Tests.

Action: Bendix

4.6 Study Plan and Test Plan: Provide inputs for the update of these plans.

Action: MSFC

4.7 Study Plan: Review the plan and determine if any changes should be made.

Action: SAO

4.8 Test Article Design: Revise the design to include thin walls between cavities. Provide the rationale for the selection of the Test Article design.

Action: Bendix

4.9 Test Article Design: Provide cavity wall dimensions from the results of the satellite design update for circular-faced retroreflectors.

Action: MSFC

4.10 Satellite Thermal Coatings: Evaluate thermal coatings of interest (Z-93, clear anodized aluminum, and bare aluminum) to determine long-term degraded characteristics for incorporation in analysis and test.

Action: MSFC

4.11 Test Article Coatings: Provide a decision on the requirement for applying the actual candidate coating on the Test Article for the Thermal/Optical Tests.

Action: MSFC

4.12 Test Article Coatings: Provide the need date for the Test Article coating decision.

Action: Bendix

4.13 Selection of Circular-Faced Retroreflectors: Document the conclusions of the Review evaluation which are the basis for selection of the circular-faced retroreflector.

Action: Bendix

4.14 Post-Vibration Test Mechanical Check: Consider a mechanical check after the final vibration test to ensure no damage has resulted.

Action: Bendix

4.15 Circular-Faced Retroreflector and Ring Mount Structural Integrity: Provide rationale, from ALSEP analysis/test data, for confidence in the structural integrity of the circular-faced retroreflector and its ring mount in the LAGEOS application.

Action: Bendix

4.16 Acoustic Environment: Provide rationale for not including exposure to the LAGEOS acoustic environment in the Vibration Test.

Action: Bendix

5. In the presentation by Mr. James McBride, MSFC, the complete LAGEOS dynamic environment was defined, for test purposes. Accordingly, it was agreed that this environment, shown in the handout in Attachment A, would be incorporated in the Study Plan Guidelines and in the Test Plan by Bendix.

JMBrunger

LAGEOS Program Manager

Table 1

List of Attendees

Bendix LAGEOS Review
17-18 April 1974

Name	Organization	Tec. No.
Donald R. Bowden	MSFC	453-2769
Bill Johnson	NASA	453-2769
Byron Crider	NASA-MSFC	453-2769
Jim McBride	NASA-MSFC	453-1330
Lewis L. McNair	NASA-MSFC	453-3490
David Arnold	SAO	617-495-7481
Lynn Lewis	BxA	313-665-7766 X560
Jim Zurasky	NASA-MSFC	205-453-4702
John Harms	BxA	313-665-7766 X
Jim Monroe	BxA	313-665-7766 X
T. E. Hoffman	SAO/Engrg.	617-495-7492
W. Lurie	SAO - Geoastronomy Programs Mgr.	617-495-7485
Ron Creel	NASA-MSFC	205-453-3851
E. Granholm	BxA	313-665-7766 X406
J. Maszatics	BxA	313-665-7766 X722
Jim McNaughton	BxA	313-665-7766 X553
John Brueger	BxA	313-665-7766 X760
Gary Ballard	BxA	313-665-7766 X255

TABLE 2

LAGEOS PROGRAM REVIEW

APRIL 17-18, 1974

BENDIX AEROSPACE SYSTEMS DIVISION
ANN ARBOR, MICHIGAN

AGENDA

• INTRODUCTION	J. BRUEGER, BXA
• THERMAL ANALYSIS	
MSFC STATUS	R. CREEL, MSFC
BENDIX RESULTS/RECOMMENDATIONS	E. GRANHOLM, BXA
• DYNAMIC ANALYSIS/TEST	
MSFC STATUS	J. McBRIDE, MSFC
BENDIX RESULTS/RECOMMENDATIONS	J. MASZATICS, BXA
• OPTICAL TESTS - MSFC STATUS	J. ZURASKY, MSFC
• SELECTION OF LAGEOS RETROREFLECTOR CONFIGURATION	MSFC/BXA
• FACILITIES TOUR	J. MONROE, BXA J. BRUEGER, BXA MSFC
• TEST PROGRAM STATUS	
TEST PROGRAM SUMMARY	J. BRUEGER, BXA
OVERALL THERMAL/OPTICAL TEST ARRANGEMENT	J. MONROE, BXA
TEST ARTICLES	J. BRUEGER, BXA
FAR-FIELD DIFFRACTION INSTRUMENT	L. LEWIS, BXA
TEST FIXTURES & EQUIPMENT	J. MONROE, BXA
THERMAL/OPTICAL TEST FIXTURE OPTICAL WINDOW AND SHIELD ASSY FFDI PLATFORM ASSY VIBRATION TEST FIXTURE TEST EQUIPMENT AND EXPENDABLES	

AGENDA (CONTINUED)

TEST CONDITIONS	J. BRUEGER, BXA
· PROGRAM SCHEDULES/STATUS	J. BRUEGER, BXA
· STUDY PLAN REVIEW	MSFC/BENDIX

Table 3

Retroreflector Trade-Off Considerations

Item	Hex CCR Advantage	Hex CCR Disadvantage	CIRC CCR Advantage	CIRC CCR Disadvantage
Thermal		Mount Thermal Contact Pressure Difficult to Control	Higher Confidence in Mount Conductance	
Optical	No Advantage to Either Approach			
Structural (Mount)		Additional Effort Required to Determine Optimum Design	ALSEP Experience; Test Results More Predictable	
Manufacturing	Less Satellite Machining			More Satellite Machining
Satellite Design				Requires Baseline Revision
Cost CCR MTG ASS Y	No Significant Differences			

Table 4

Retroreflector Evaluation Conclusions

Bendix Evaluation Conclusions: Select Circular (ALSEP-Type) Retroreflector

Thermal:

Circular (ALSEP) is best (by analysis results). Hex (GEOS-type) will approach the circular retroreflector thermal performance, if optimized; but no advantage is expected for this effort (i. e., do not expect to get better thermal performance from Hex).

Optical:

Circular (ALSEP) is easier to analyze at SAO.
ALSEP optical analysis experience at Itek provides increased confidence in data
Circular (ALSEP) has optical performance proven in the lunar application (Apollo 11, 14 and 15 flights)
Test program is required to provide comparative optical data of Circular vs. Hex for LAGEOS.

Structural:

ALSEP experience in test and flight is applicable for confidence in structural integrity.
Hex mount design requires additional design, analysis and test effort to optimize design (for thermal and structural requirements).

Manufacturing:

ALSEP experience: existing drawings and procedures, while not directly applicable, provide more confidence that unexpected problems are not likely to arise, even though there are unique LAGEOS requirements.
ALSEP design: proven tolerances and alignment integrity.
ALSEP installation in satellite is basically simpler; the optimized hex corner/clip assembly may require additional tooling for installation in satellite.

Satellite Design:

ALSEP and Hex are comparable in the ability to control retroreflector apex location for center of mass control.

Costs:

ALSEP retroreflectors, mount hardware and assembly costs are comparable to Hex.

ATTACHMENT A

MSFC PRESENTATION HANDOUTS

Bendix LAGEOS Phase B Program Review
17-18 April 1974

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: R. CREEL
S&E-ASTN-PF	LAGEOS THERMAL CONTROL	DATE: APRIL 17, 1974

INTRODUCTION

- BASIC OBJECTIVES
    - USE RESULTS TO DEFINE TEST PROGRAM REQUIREMENTS
    - BENDIX ANALYZING TRANSIENT SATELLITE THERMAL RESPONSE AND AVERAGE CCR TEMPERATURES
    - MSFC ANALYZING STEADY-STATE TEMPERATURE GRADIENTS IN ONE DETAILED CCR
- COMMON ASSUMPTIONS
    - 5900 KM ORBIT ALTITUDE, 90° INCLINATION
    - SPIN RATE = 0.0 RPM (WORST CASE)
    - SPIN AXIS ORIENTATION NOT FIXED

ORGANIZATION: S&E-ASTN-PF	MARSHALL SPACE FLIGHT CENTER LAGEOS THERMAL ANALYSES	NAME: R. CREEL DATE: APRIL 17, 1974

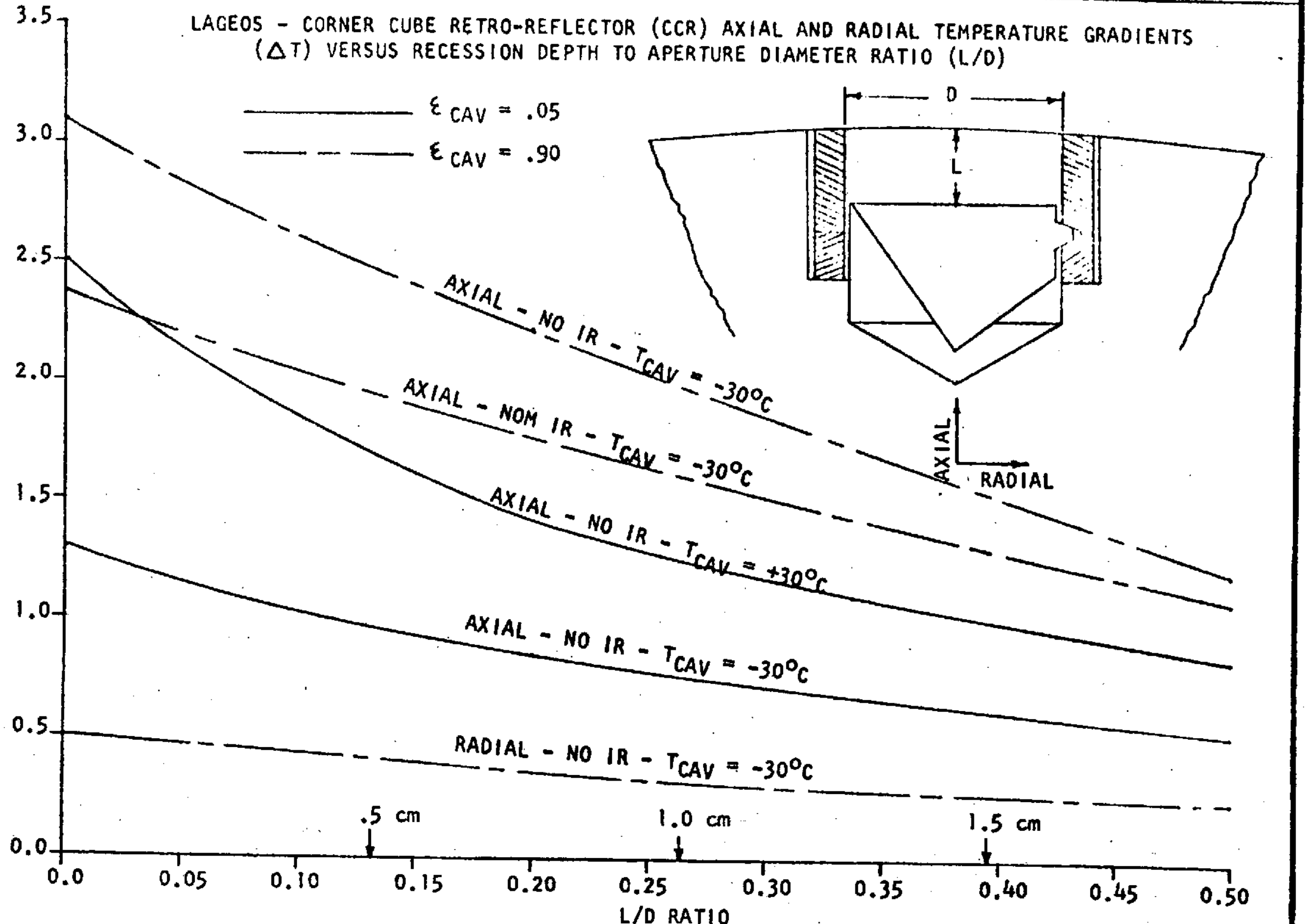
RESULTS

- GRADIENTS (DEG. C) - WITH NO RECESSION, $-30^{o}C$ SATELLITE, NO IR HEATING

	$\epsilon_{CAV} = 0.90$	$\epsilon_{CAV} = .05$
• AXIAL (APEX TO FRONT FACE)	3.10	1.29
• RADIAL (CENTER TO SIDE)	0.50	0.15

- MINIMIZE GRADIENTS BY
  - RECESSION OF CCR'S
  - LOWER SATELLITE TEMPERATURE
  - LOWER CAVITY EMITTANCE
  - INCREASE IR HEATING (CAN'T BE CONTROLLED)

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: R. CREEL
S&E-ASTN-PF	LAGEOS THERMAL ANALYSES	DATE: APRIL 17, 1974



SATELLITE SURFACE OPTICAL PROPERTIES

- DESIRED PROPERTIES
  - STABILITY OVER LONG LIFETIME
  - LOW SOLAR ABSORPTANCE, α_s
  - HIGH INFRARED EMITTANCE, ε_{IR}
  - NO OUTGASSING OR DEGRADATION
- CANDIDATES

CANDIDATES	$\alpha_s / \varepsilon_{IR}$
ANODIZED ALUMINUM	.57
SANDBLASTED ALUMINUM	2.00
PORCELAIN ENAMEL	.25
Z-93 PAINT	.24

- PRELIMINARY CONCLUSIONS
  - STABLE $\alpha_s / \varepsilon_{IR}$ BELOW 1.0 IS QUESTIONABLE
  - ANODIZED IS MOST PROMISING

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME:
S&E-ASTN-PF	LAGEOS THERMAL ANALYSES	R. CREEL
		DATE: APRIL 17, 1974

RECOMMENDED TEST VARIABLES

- RECESSION DEPTH
- CAVITY EMITTANCE
- SATELLITE TEMPERATURE

FUTURE EFFORTS

- GENERATE DETAILED THERMAL TRANSIENT MODEL
- PREDICTIONS FOR TEST CONDITIONS
- SELECT RECESSION DEPTH
- SELECT SURFACE COATINGS

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME
ASTRONAUTICS LABORATORY S&E-ASTN-AD	DYNAMIC QUALIFICATION CRITERIA	J. E. McBRIDE DATE

SINE VIBRATION TEST - 3 AXES

5 - 16 HZ AT 2.3 G PEAK
16 - 22 HZ AT 6.8 G PEAK
22 - 100 HZ AT 2.3 G PEAK

SWEEP RATE: 2 OCTAVES/MINUTE

SHOCK TEST (SINE SWEEP) - 3 AXES

200 - 2,000 G AT 5 G PEAK

SWEEP RATE: 2 OCTAVES/MINUTE

RANDOM VIBRATION TEST

20 - 300 HZ AT +3 dB/OCTAVE
300 - 2,000 HZ AT 0.05 G^2/HZ

TEST DURATION: 2 MINUTES/AXIS

9.8 G_{RMS}

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME:
ASTRONAUTICS LABORATORY S&E-ASTN-AD	EARLY DEVELOPMENT DYNAMIC TEST	J. E. McBRIDE DATE:

TEST SPECIMEN

SINGLE RETROREFLECTOR CUBE AND CLIP MOUNTED ON A FLAT PLATE (NO RECESS HOLE).

PURPOSE

-- TO DETERMINE THE NATURAL FREQUENCIES AND RESPONSE AMPLITUDES OF THE SPECIMEN.

-- TO DETERMINE IF THERE ARE POTENTIAL INTERFERENCE PROBLEMS BETWEEN THE RETROREFLECTOR AND MOUNTING HOLE

TEST

-- SPECIMEN WILL BE TESTED TO THE LAGEOS DYNAMIC QUALIFICATION CRITERIA.

-- TESTS WILL BE CONDUCTED WITH SCREW ONLY MOUNTING AND WITH SCREW AND WASHER MOUNTING.

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: J. ZURASKY
S&E-ASTR-RPO	LAGEOS	DATE: APRIL 17, 1974

IN-HOUSE TASKS

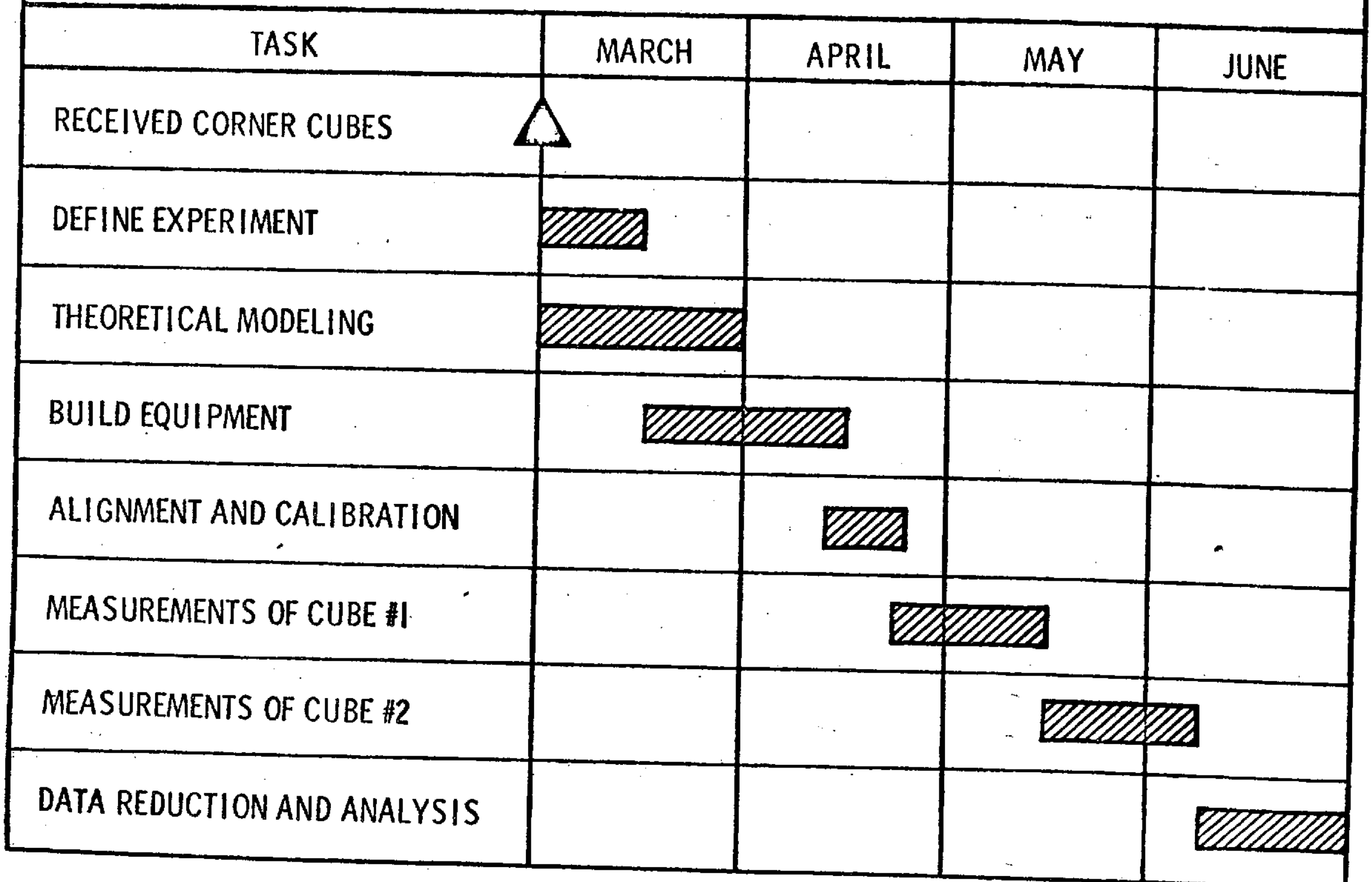
- RETURN BEAM AS A FUNCTION OF
  - INCIDENT ANGLE
  - RECESS DEPTH
  - POLARIZATION
- SUPPLEMENT SMITHSONIAN CALCULATIONS
  - FAR-FIELD DIFFRACTION PATTERNS
  - PHOTO-ELECTRON RETURN AS A FUNCTION OF
    - ALTITUDE
    - ORIENTATION
  - BAKER-NUNN IMAGERY

MSFC - Form 3304 (Rev October 1972)

FILE

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: J. ZURASKY
S&E-ASTR-RPO	LAGEOS	DATE: APRIL 17, 1974

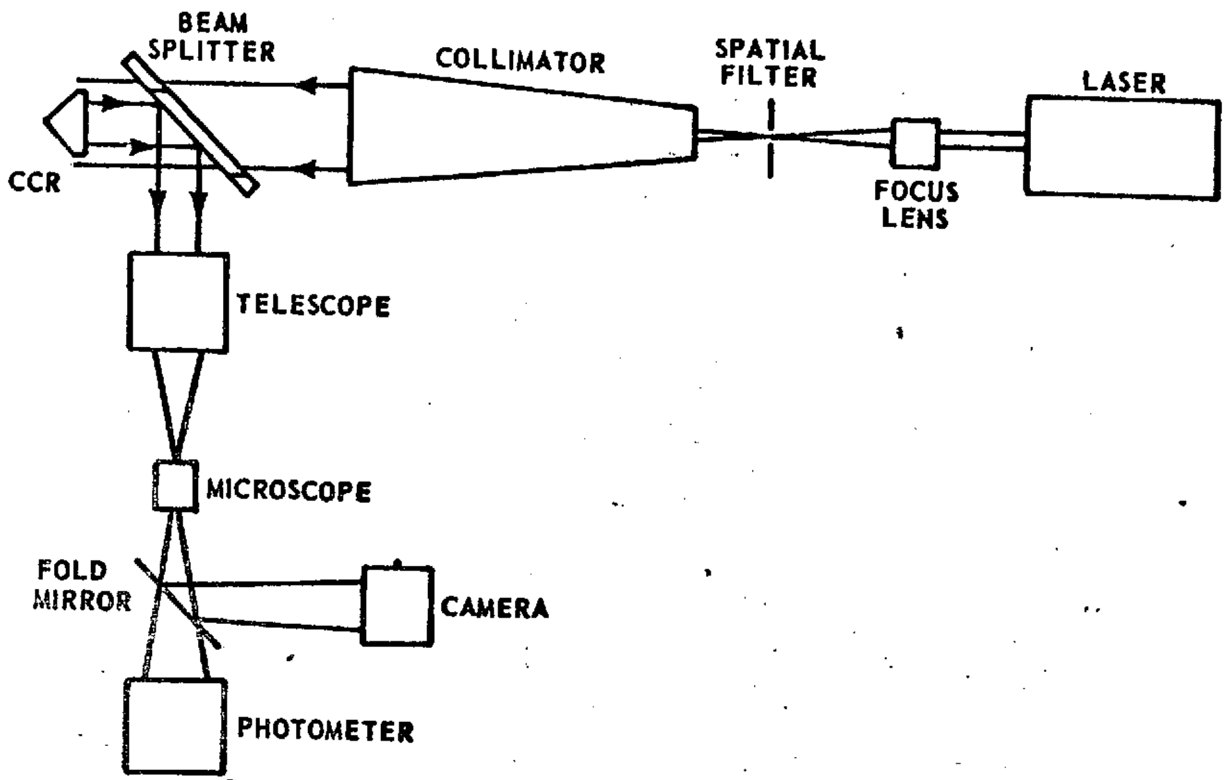
IN-HOUSE CORNER CUBE ANALYSIS



MSFC - Form 3384 (Rev October 1970)

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: J. ZURASKY
S&E-ASTR-RPO	LAGEOS	DATE: APRIL 17, 1974

FAR FIELD DIFFRACTION TEST APPARATUS



Internal
Memorandum

APPENDIX C

Bendix Aerospace Systems Division

Ann Arbor, Michigan

Date 15 July 1974 Letter No. LAGEOS - 38

To J. Brueger

From E. Granholm

Subject LAGEOS, Thermal Analysis of Recessed Retroreflector

Reference: LAGEOS-24, "LAGEOS Thermal Optical Test, Retroreflector and Mount Thermal Performance," dated 30 May 1974.

The objective of this analysis is to determine the amount of retroreflector thermal performance improvement which can be achieved by recessing the corner within its cavity. The retroreflector/cavity mathematical model (Reference) used to predict thermal performance for the 1.0 mm corner face recession was modified to analyze a recession depth of 1.0 cm. The retroreflector and associated mount were evaluated for various solar and IR heating conditions. Thermal finishes/coatings of bare, machined aluminum and Z-93 were also considered.

A direct thermal performance comparison between the 1.0 mm and 1.0 cm recessed retroreflectors is presented in Table 1. The maximum radial and axial corner temperature gradients are 0.9 and 1.4°C, respectively for the bare aluminum finish, sun/no IR environment and the 1.0 cm recession depth case. The gradients are reduced approximately 25% from their corresponding previous levels of 1.3 and 1.9°C, respectively for 1.0 mm recession. The other cases shown in Table 1 also indicate a reduction in axial and radial gradients attributed to the 1.0 cm recession.

However, previous studies conducted by MSFC showed that for a 1.0 cm recession (L/D $\approx$ 25%) the strength of the LAGEOS satellite optical return could be reduced by 30%. Therefore, the extent of optical performance improvement due to reduction of retroreflector temperature gradients must be traded-off against optical performance degradation due to obscuration.

E. Granholm

E. Granholm

D. Fithian
K. Hsi
S. Krajewski
L. Lewis
J. Maszatics
J. Monroe
J. McNaughton

TABLE 1

THERMAL PERFORMANCE FOR RECESSED RETROREFLECTORS

Environmental Condition	Recess Depth	Cavity Temp	Retro Face Temp	Lower Ring Temp	Upper Ring Temp	Retainer Ring Temp	ΔTaxial	ΔTradial
No Sun, No IR (Bare AL)	1.0 cm	+30°C	- 7.2°C	29.8°C	14.7°C	14.6°C	1.2°C	0.8°C
	1.0 mm	+30°C	-20.9°C	29.8°C	12.4°C	12.4°C	1.6°C	1.1°C
Sun, No IR (Bare AL)	1.0 cm	+30°C	18.3°C	30.1°C	52.5°C	52.7°C	1.4°C	0.9°C
	1.0 mm	+30°C	2.8°C	30.1°C	51.1°C	51.3°C	1.9°C	1.3°C
No Sun, IR (Bare AL)	1.0 cm	+30°C	2.1°C	29.9°C	17.7°C	17.7°C	0.9°C	0.6°C
	1.0 mm	+30°C	-12.1°C	29.8°C	14.9°C	14.9°C	1.4°C	0.9°C
No Sun, No IR (Z-93)	1.0 cm	-30°C	-60.6°C	-30.2°C	-54.4°C	-54.5°C	0.5°C	0.3°C
	1.0 mm	-30°C	-69.0°C	-30.2°C	-48.4°C	-48.9°C	0.7°C	0.5°C
Sun, No IR (Z-93)	1.0 cm	-30°C	-37.9°C	-30.0°C	-33.7°C	-33.7°C	0.7°C	0.0°C
	1.0 mm	-30°C	-46.9°C	-30.0°C	-26.4°C	-26.3°C	1.0°C	0.4°C
No Sun, IR (Z-93)	1.0 cm	-30°C	-45.7°C	-30.1°C	-47.5°C	-47.6°C	0.2°C	0.1°C
	1.0 mm	-30°C	-53.7°C	-30.1°C	-42.3°C	-43.3°C	0.4°C	0.3°C

Memorandum

Aerospace Systems Division

Ann Arbor, Michigan

Date 28 May 1974

Letter No. 74-520-215
LAGEOS-23

To Distribution

From E. Granholm

Subject LAGEOS Thermal/Optical Analysis, Maximum Retroreflector Temperature Gradients

Reference: LAG-3 (Rev A), "LAGEOS Thermal/Optical Analysis Statement of Work", dated 26 April 1974.

A thermal analysis was performed to determine the LAGEOS retroreflector maximum axial and radial temperature gradients. The enclosed information is to be used by Itek for the generation of optical performance data as specified by Paragraph 2.3 of the referenced document.

Boundary conditions assumed in the analysis reflect the 4 x 8 foot chamber thermal environment which is defined by Table 1 below. The levels presented will promote maximum temperature gradients in the retroflector.

Table 1

Retroreflector Thermal Analysis Environmental Conditions

Condition	Level
Pressure	1×10^{-6} torr
Cryowall	-185°C
Retroreflector Cavity Temperature	30°C
Retroreflector/Cryowall View Factor	1.00
Solar and IR Input	Full solar, no IR

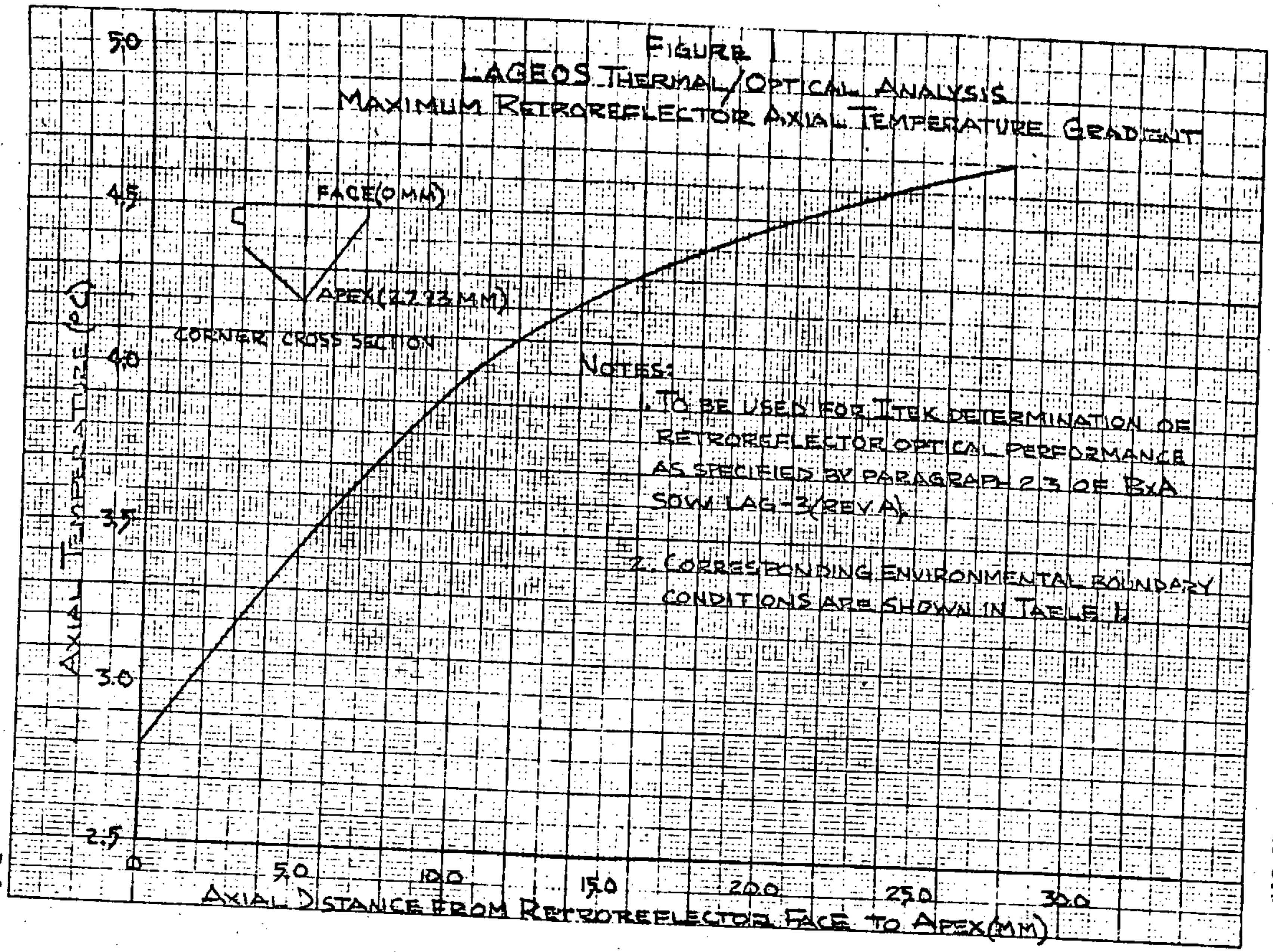
For a 30°C cavity temperature the retroreflector face and apex temperature levels are 2.8 and 4.7°C respectively. The corresponding axial temperature gradient of 1.9°C is shown in Figure 1.

Radial temperature gradients through the retroreflector at various levels are given in Figure 2. The corner tab and face center temperatures are 4.1 and 2.8°C, respectively (1.3 °C gradient). Radial temperature gradients are maximum at the corner face and progressively decrease at each receding level.

Optical performance results calculated by using Figure 1 and 2 temperature gradients will be compared with FFDI measurements obtained during thermal vacuum testing. Correlation of data will give a level of confidence that orbital optical performance for LAGEOS can be accurately predicted.

E. Granholm
E. Granholm

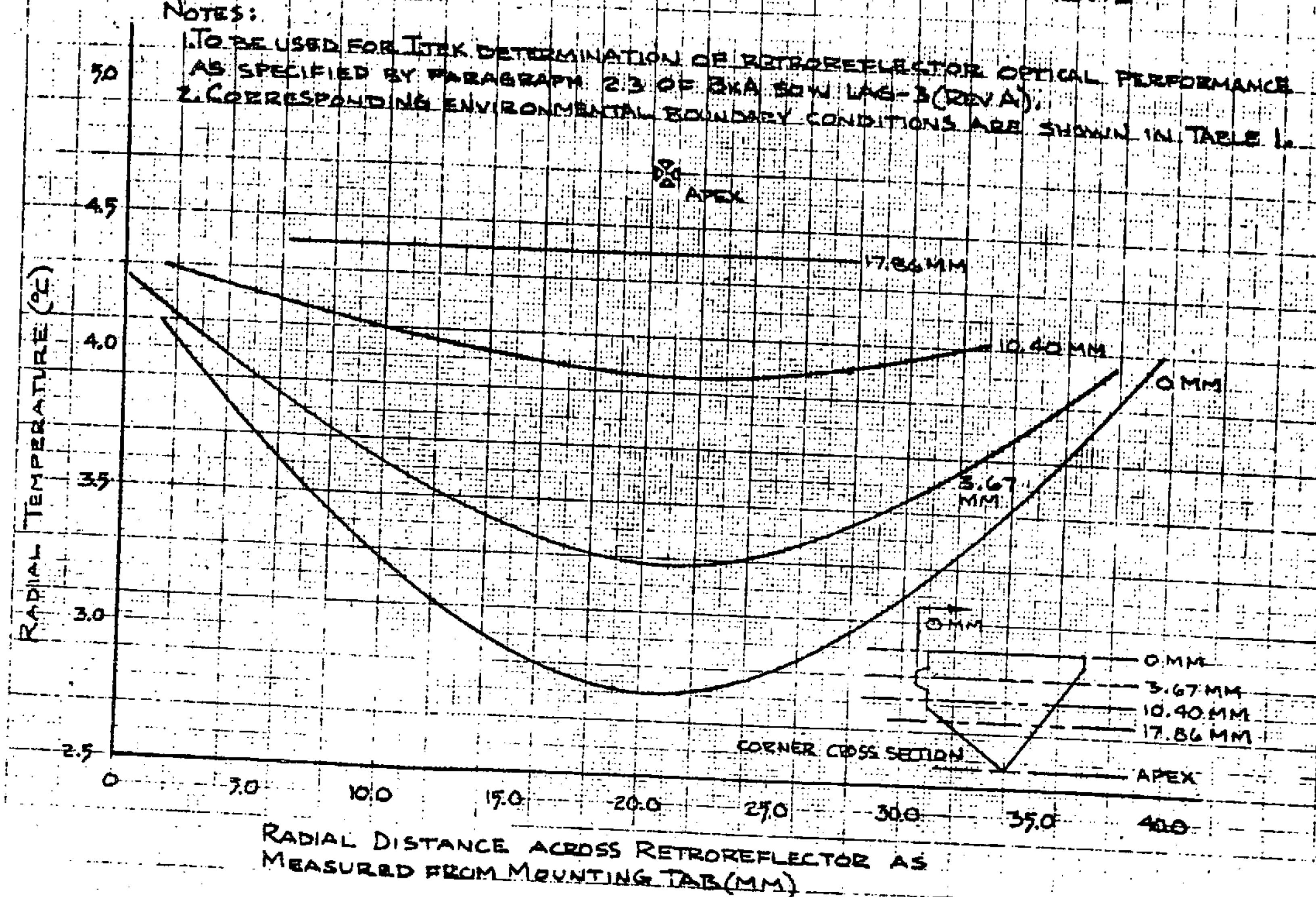
Distribution:
- J. Brueger
- D. Fithian
- L. Lewis
- J. McNaughton
- J. Maszatics
- J. Monroe
- J. Riley



Attachment to Memo 74-520-215

FIGURE 2
LAGEOS THERMAL/OPTICAL ANALYSIS
MAXIMUM RETROREFLECTOR RADIAL TEMPERATURE GRADIENTS

NOTES:
1. TO BE USED FOR TJEK DETERMINATION OF RETROREFLECTOR OPTICAL PERFORMANCE AS SPECIFIED BY PARAGRAPH 2.3 OF BXA SOW LAG-3 (REV A).
2. CORRESPONDING ENVIRONMENTAL BOUNDARY CONDITIONS ARE SHOWN IN TABLE 1.



Attachment to Memo 74-520-215

EAG 5.28.74

Memorandum

Aerospace Systems Division
Ann Arbor, Michigan

Date 30 May 1974 Letter No. LAGEOS-24

To J. Brueger

From E. Granholm

Subject LAGEOS Thermal/Optical Test, Retroreflector and Mount Thermal Performance

Reference: MSFC Drawing Number 50M23161, "Corner Cube Mount Assembly", Rev. A, dated 24 April 1974

Introduction:

A detailed thermal analysis was performed on the reference retroreflector and mount designs supplied by MSFC. The 4 x 8 foot T/V chamber and Genarco carbon arc lamp constituted the simulated space environment imposed on the mount assembly. The satellite conductive and radiative heat transfer interface was simulated by a 6061-T6 aluminum mounting cavity which was temperature controlled.

The retroreflector and associated mount were thermally analyzed for various solar and IR heating conditions. The objective of the analysis is to determine the thermal environment which causes maximum retroreflector temperature perturbation and to define the corresponding corner axial and radial temperature gradients. The resulting thermal data will be used in optical analyses to be conducted which will predict the lower-limit retroreflector performance.

Summary:

Results of the retroreflector mount assembly thermal analysis for the T/V test conditions indicate that the full sun, no IR environment coupled with the +30°C cavity temperature promote upper-bound temperature gradients in the corner. The 30°C cavity temperature was estimated based on an exterior satellite surface of bare machined aluminum. For the above conditions the retroreflector face and apex temperatures are 2.8 and 4.7°C, respectively (a 1.9°C axial temperature gradient). Since the corner tab temperature is 4.1°C, the maximum radial gradient is 1.3°C.

Analysis:

The following assumptions were made for purposes of thermal analysis:

1. The configuration of the retroreflector mount assembly was as described by the referenced MSFC drawing. Details of the mount are shown in Figure 1.

2. A +30°C cavity temperature corresponded to a satellite exterior surface of bare, machined aluminum (α/ϵ = .37/.05).

3. A -30°C cavity temperature corresponded to a satellite exterior surface of IIT's Z-93 thermal control coating (α/ϵ = .2/.9).

4. The cavity IR emittance was assumed to be 0.05.

5. A 0.08 mm gap existed between the retroreflector tab and the upper Kel "F" ring. The retroreflector rested on the lower ring.

6. The chamber pressure and cryowall temperature were 1×10^{-6} torr and -185°C, respectively.

7. The retroreflector face/cryowall wall view factor was 100%.

8. The incident solar constant was 1397 watts/m^2.

9. The incident maximum IR heat load was 66.5 watts/m^2.

In general, thermal/mechanical properties of the mounting rings, retainer ring and retroreflector were selected to yield upper-bound temperature gradients in the corner. A steady-state thermal model was used to generate retroreflector and mount assembly temperature levels.

Results:

Results showing thermal performance of the corner cube mount assembly for six thermal/vacuum test conditions are presented in Table 1. The environmental condition of full sun with no IR coupled with a 30°C cavity temperature (Case 1) promotes maximum axial and radial temperature gradients of 1.9 and 1.3°C, respectively. For the same environment but at a lower cavity temperature of -30°C (Case 2) the corresponding gradients are reduced to 1.0°C and 0.4°C, respectively.

For the no sun, no IR conditions (Cases 3 and 4) axial temperature gradients are slightly reduced when compared to the corresponding solar Cases 1 and 2. Corner radial temperature gradients remain approximately unchanged for the solar and non solar conditions. Cases 5 and 6 show that the lowest corner temperature gradients result when the corner cube assembly is exposed to one equivalent earth IR input with no solar heat load.

Conclusions:

Thermal performance for the corner cube mount assembly as shown in Table 1 indicates that as cavity temperature decreases retroreflector temperature gradients also decrease. Thermal coatings having low solar absorptance and high IR emittance values should therefore be applied to the satellite exterior surface to minimize retroreflector temperature gradients.

Case 1 thermal conditions induce maximum axial and radial temperature gradients in the retroreflector. An optical analysis incorporating Case 1 temperature gradients will predict the retroreflector lower-limit performance level.

E. Granholm

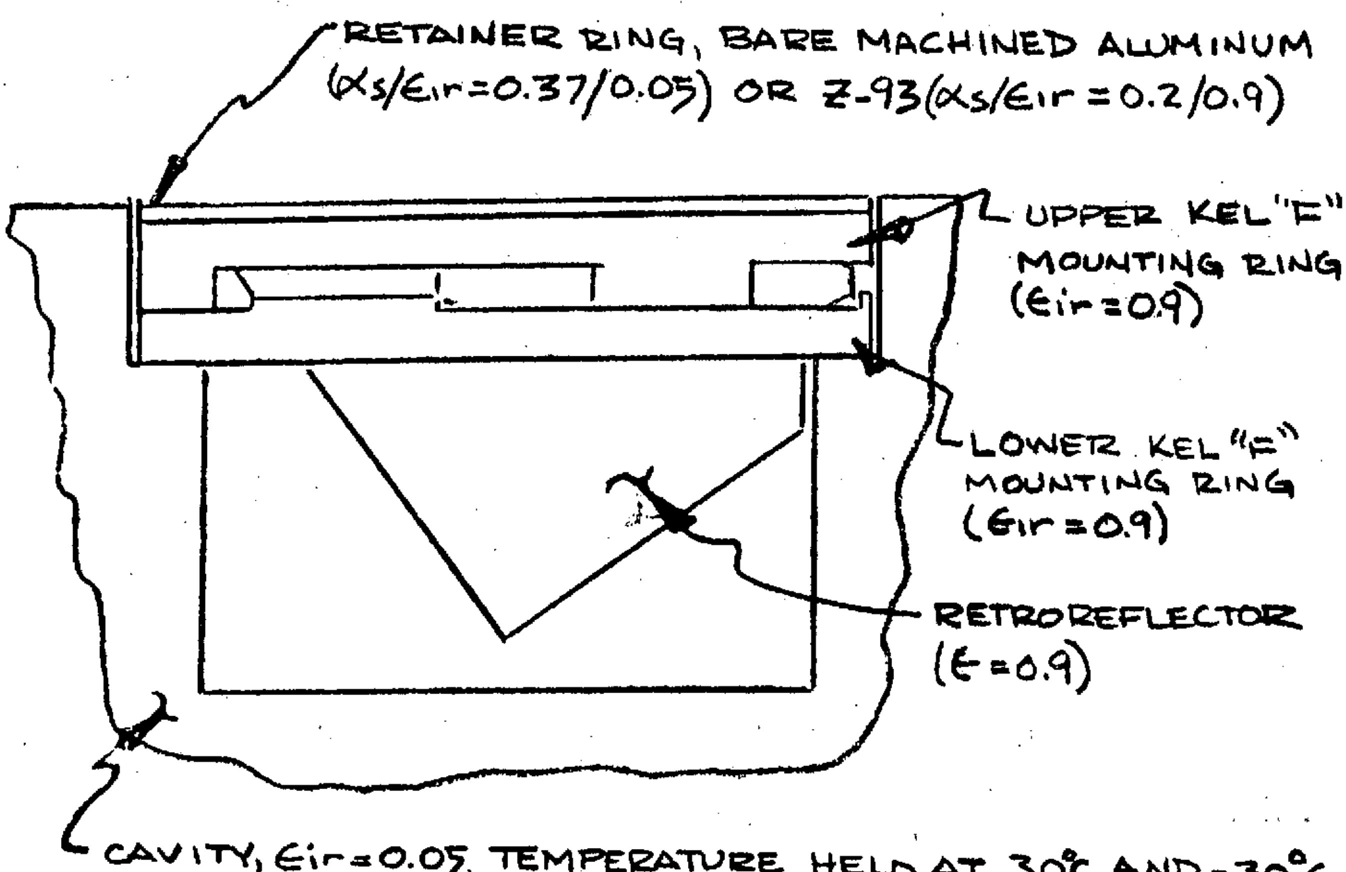
E. Granholm

cc: D. Fithian
L. Lewis
J. Maszatics
J. McNaughton
J. Monroe

FIGURE 1

RETROREFLECTOR AND MOUNT ASSEMBLY

MSFC DWG NO 50M23161



NOTES:

1. RING ASSEMBLY IS HARD MOUNTED TO CAVITY SHOLDER WITH 3/#2-56 SCREWS.

2. GAP OF 0.08 MM BETWEEN RETROREFLECTOR TAB AND UPPER KEL "F" RING.

3. RETROREFLECTOR TAB RESTS ON LOWER KEL "F" RING.

Table 1

Retroreflector and Mount T/V Test Thermal Performance

Case	Condition	Cavity Temp	Retro Face Temp	Lower Kel F Ring Temp	Upper Kel F Ring Temp	Retainer Ring Temp	Retro ΔT Axial	Retro ΔT Radial
1	Sun, No IR	+30°C	2.8°C	30.1°C	51.1°C	51.3°C	1.9°C	1.3°C
2	Sun, No IR	-30°C	-46.9°C	-30.0°C	-26.4°C	-26.3°C	1.0°C	0.4°C
3	No Sun, No IR	+30°C	-20.9°C	29.8°C	12.4°C	12.4°C	1.6°C	1.1°C
4	No Sun, No IR	-30°C	-69.0°C	-30.2°C	-48.4°C	-48.9°C	0.7°C	0.5°C
5	IR, No Sun	+30°C	-12.1°C	29.8°C	14.9°C	14.9°C	1.4°C	0.9°C
6	IR, No Sun	-30°C	-53.7°C	-30.1°C	-42.3°C	-43.3°C	0.4°C	0.3°C

NOTES:

1. All T/V testing is to be conducted in 4 x 8 ft chamber.
2. Cavity Temperatures :
   a. +30°C corresponds to bare, machined aluminum retainer ring and satellite exterior surface (estimated).
   b. -30°C corresponds to IIT's Z-93 thermal coating applied to exterior surfaces of retainer ring and satellite (estimated).

Internal
Memorandum

APPENDIX F

Bendix Aerospace Systems Division

Date 10 June 1974 Letter No. LAGEOS-29 Ann Arbor, Michigan

To J. Brueger

From E. Granholm

Subject LAGEOS, Transmission of Retroreflector Temperature Gradient Data to Itek

Reference: LAGEOS-27, "Optical Analysis Plan Summary", dated 3 June 1974

This memorandum presents the entire set of retroreflector temperature gradient data specified by the referenced document. The information is to be used by Itek for the analytical generation of retroreflector optical performance levels.

The enclosed retroreflector temperature gradient plots (Figures 1-8) are consistent with the cases called out by the analysis plan. The case number, description, differential temperature data, and the applicable Figure are tabulated below:

Case	Description	ΔT Axial, °C	ΔT Radial, °C	Applicable Figure(s)
2.3.a.1	Z93 coating on retrainer ring, -30° cavity, full sun, no IR	1.0	0.4	Fig. 1 & 2
2.3.a.2	Estimated maximum retroreflector temp. gradients	3.5	2.0	Fig. 3 & 4
2.5.a	Unit axial temperature gradient	2.0	0	Figure 5
2.5.b	Unit radial temperature gradient	0	2.0	Figure 6
2.3.b 2.4.b.2	Bare machined aluminum retainer ring, +30°C cavity, full sun, no IR	1.9	1.3	Fig. 7 & 8

The above data was transmitted to Itek on the following dates:

Figure(s)	Date Transmitted
1 - 4	3 June 1974 (Air Mail)
5 - 6	7 June 1974 (Telefax)
7 - 8	28 May 1974 (Air Mail)

As of 7 June 1974 M. Kahan (Itek) had confirmed the receipt of the entire set of retroreflector temperature gradient data. The arrival dates at Itek complied with the LAGEOS Program schedule.

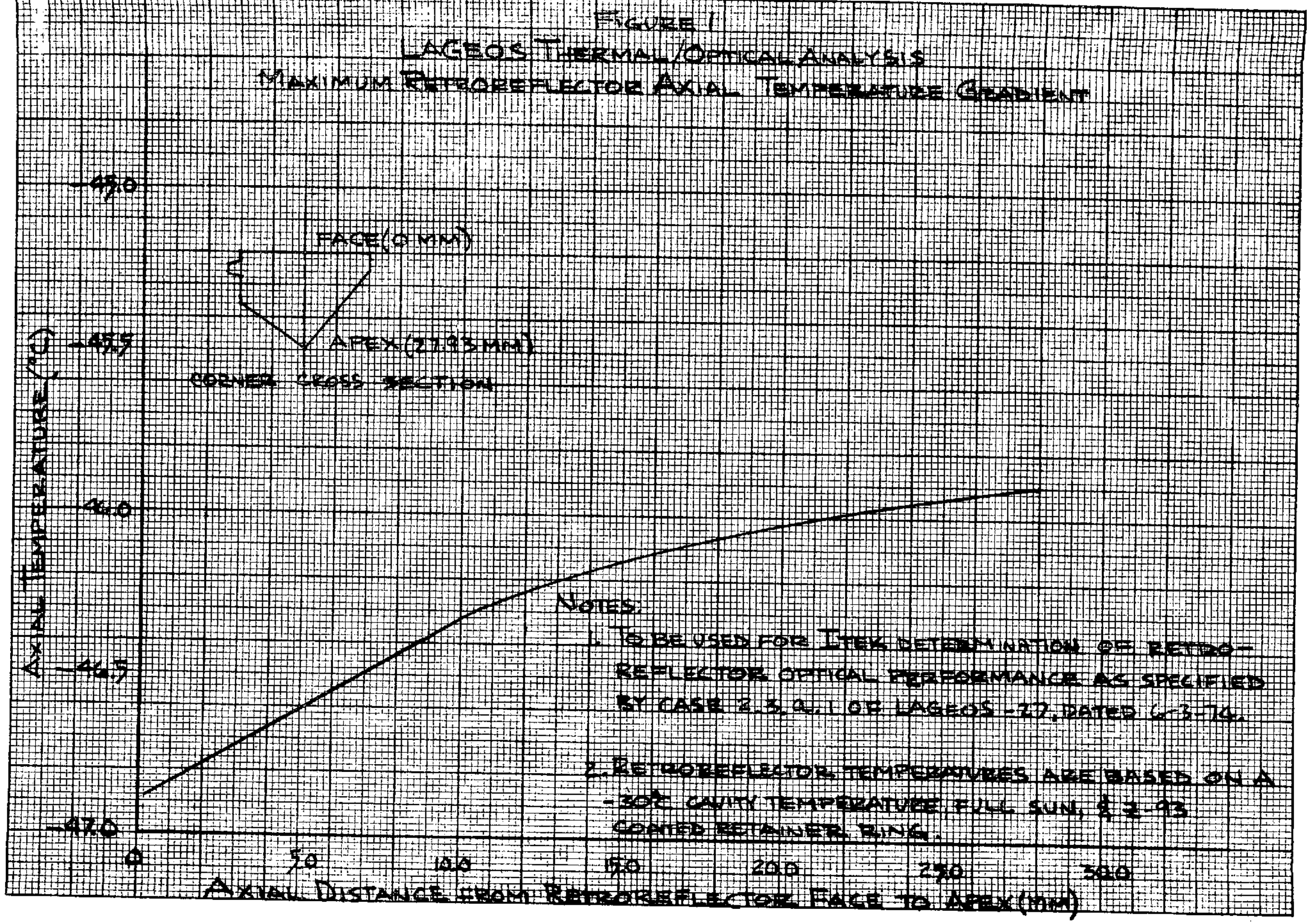
E. Granholm

E. Granholm

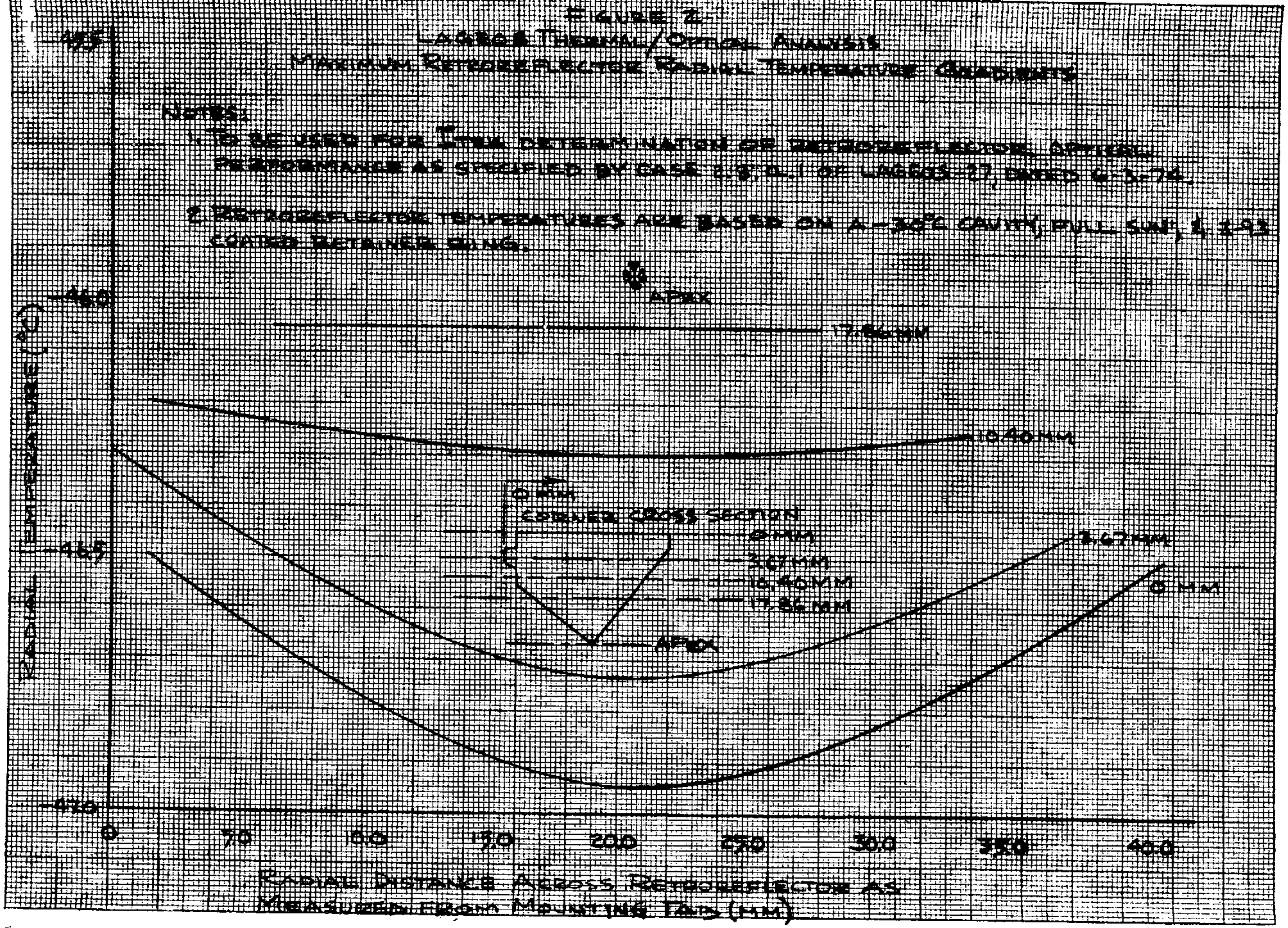
EG:b

cc: D. Fithian
S. Krajewski
L. Lewis
J. Maszatics
J. Monroe
J. McNaughton
J. Riley

Attachments



Attachment to Memo LAGEOS-29



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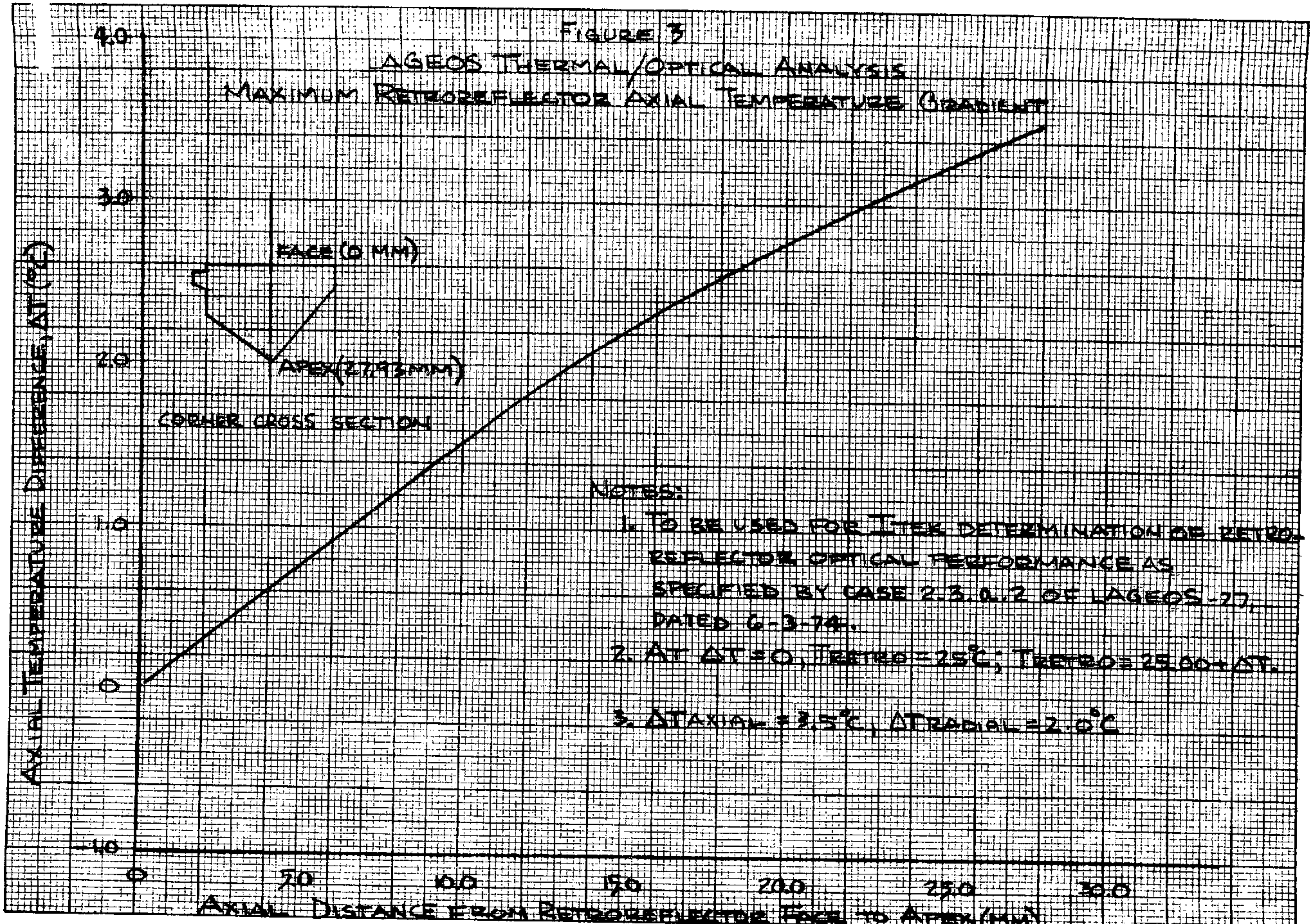

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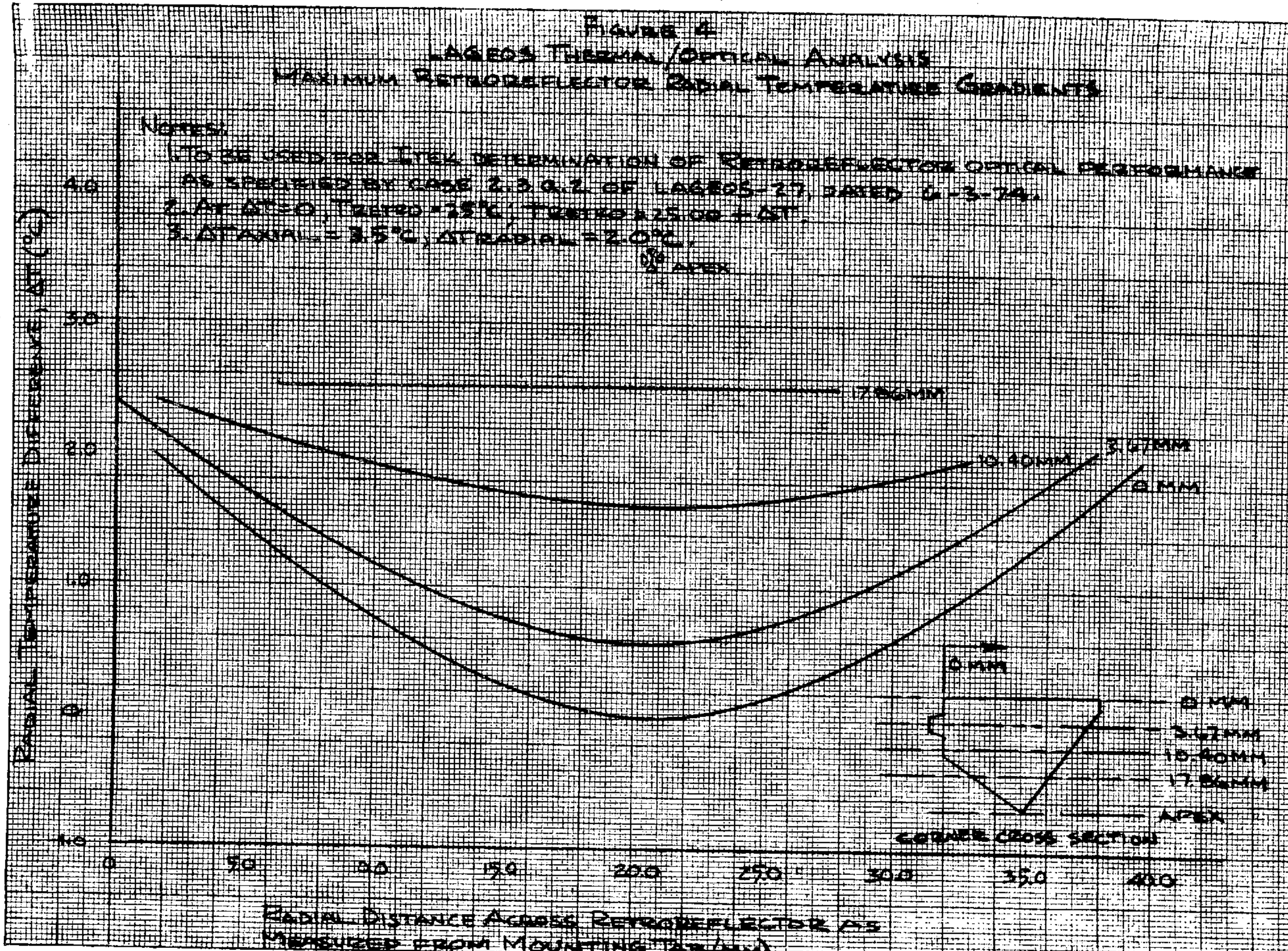
EAG 6-3-74



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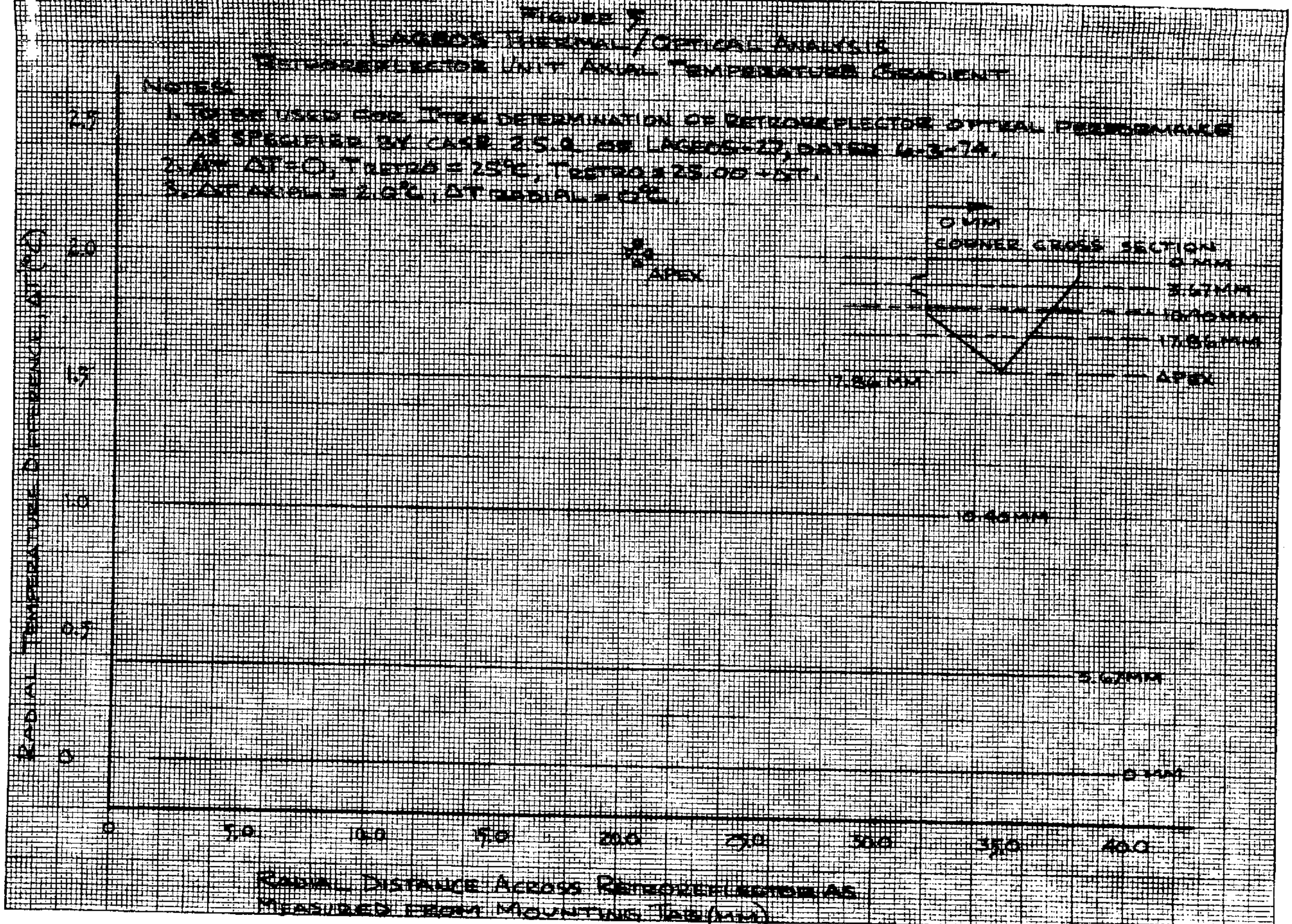

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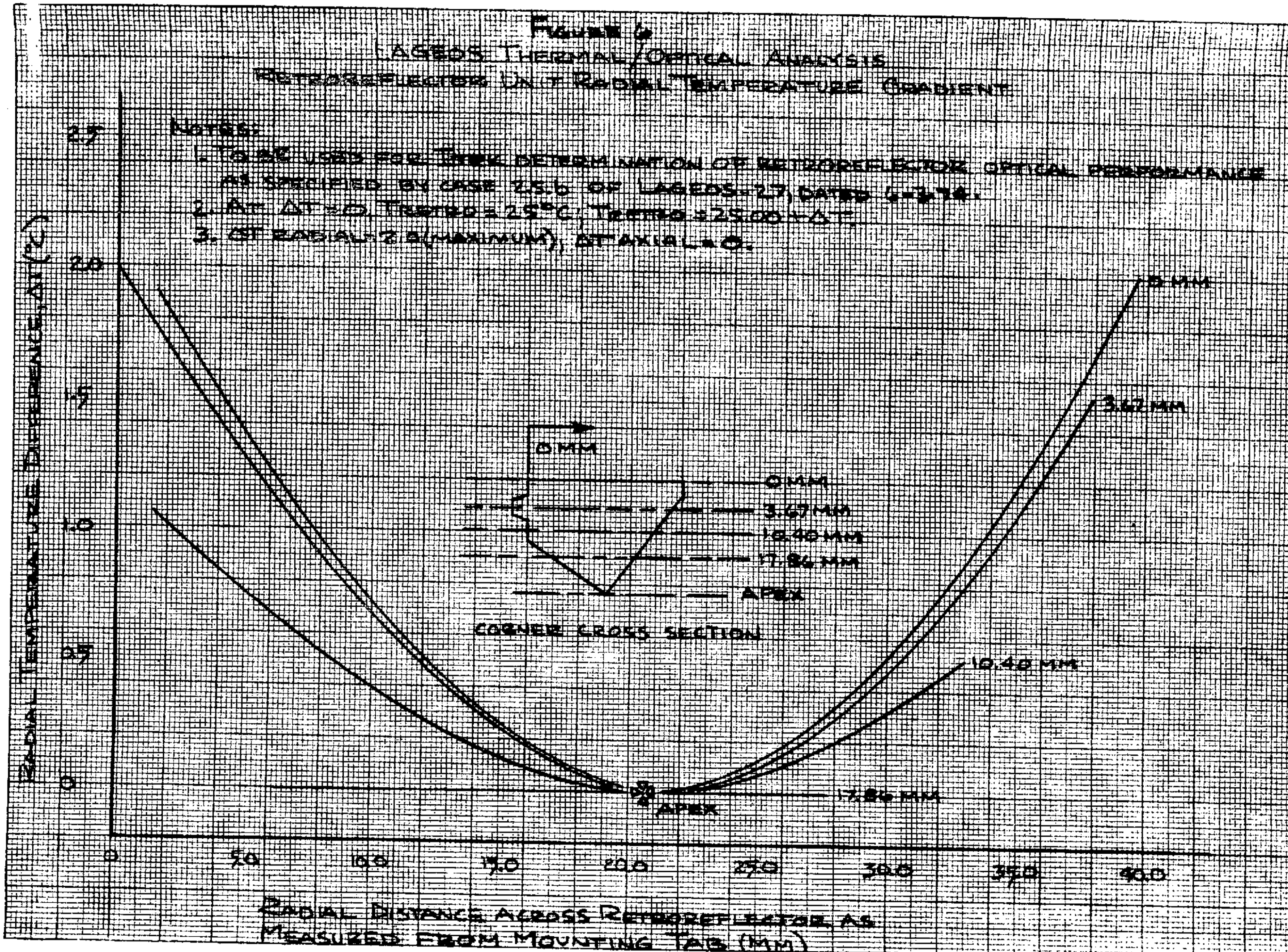
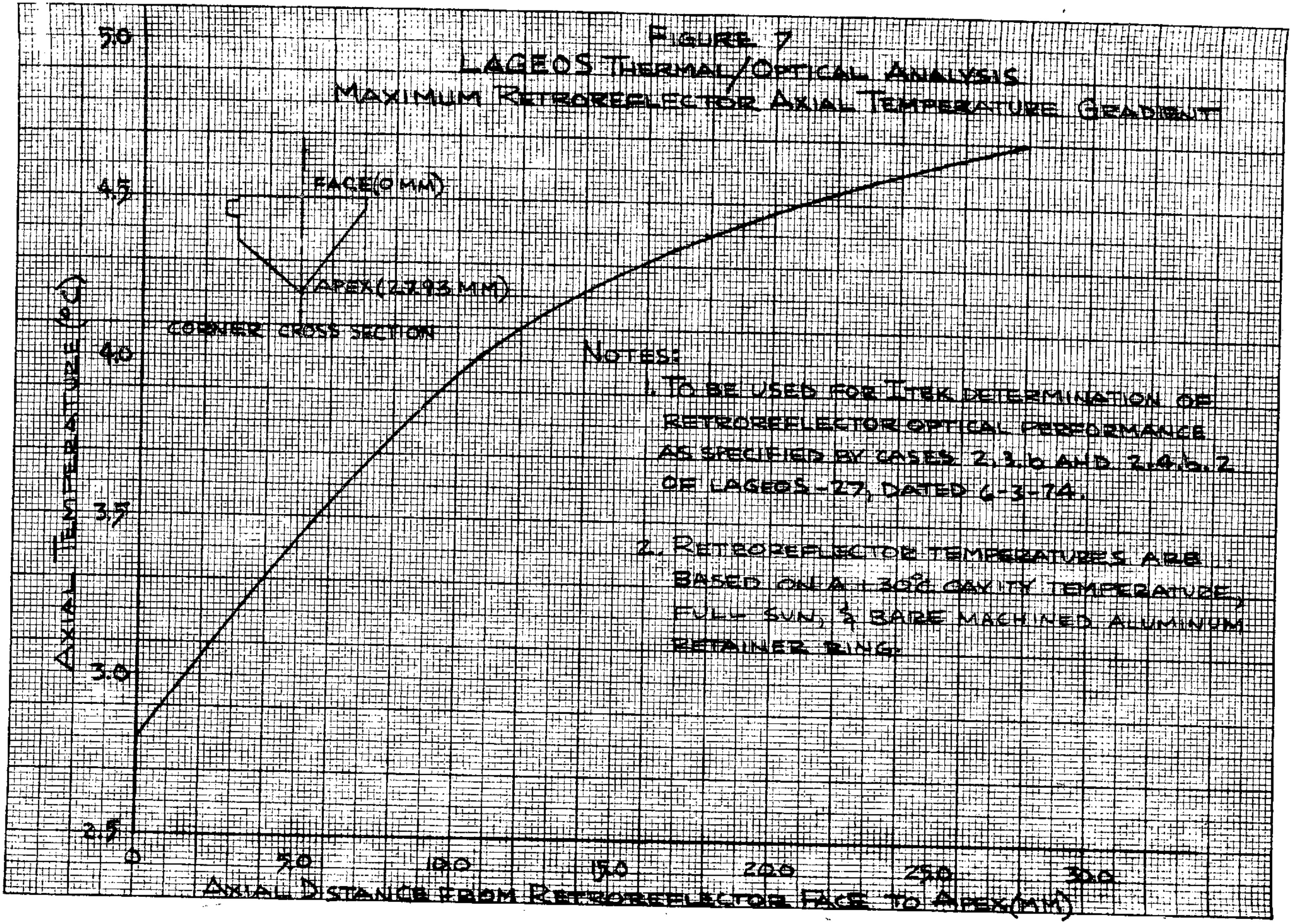
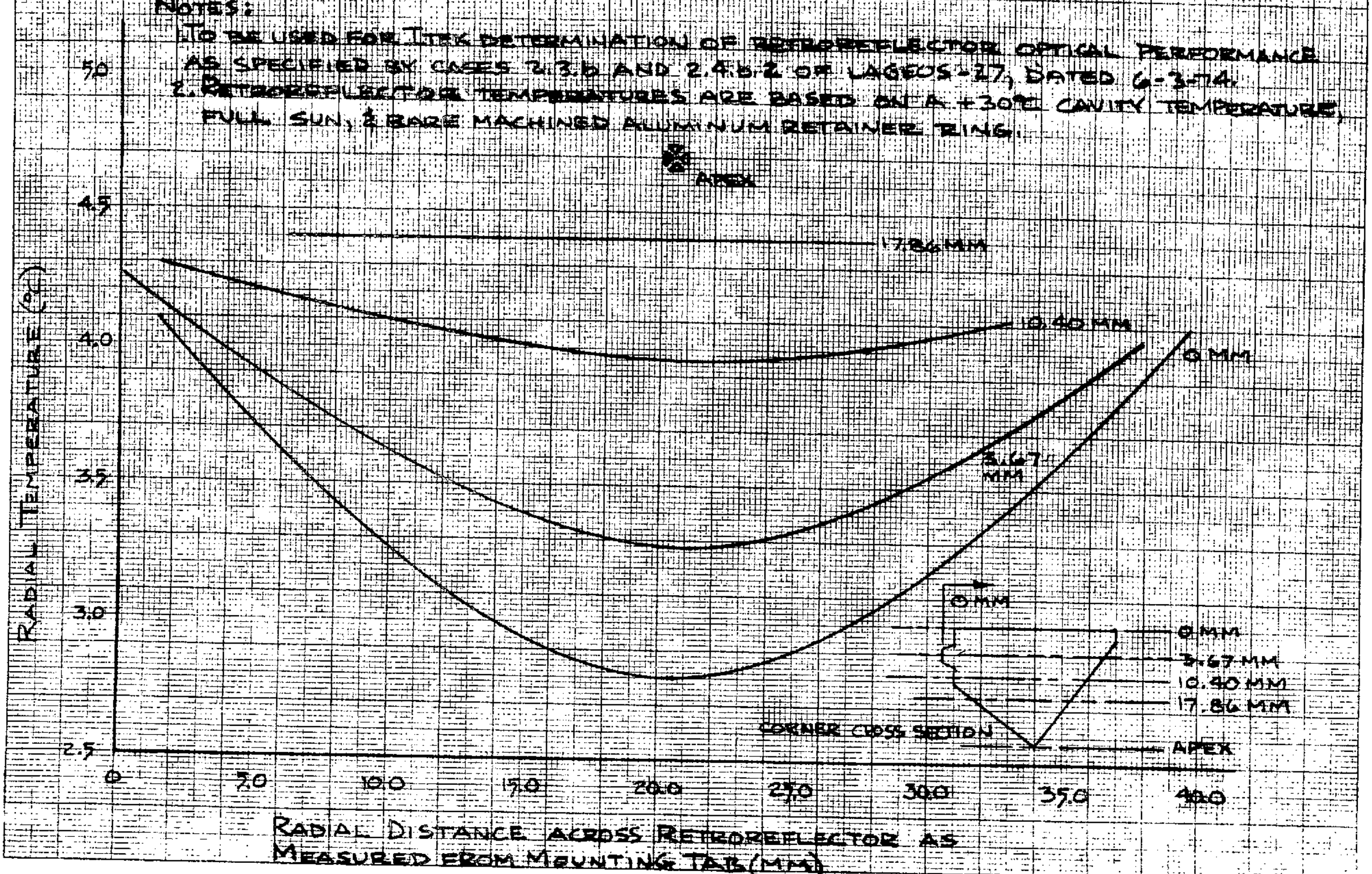


Attachment to Memo LAGEOS-29



Attachment to Memo LAGEOS-29

FIGURE 8
LAGEOS THERMAL/OPTICAL ANALYSIS
MAXIMUM RETROREFLECTOR RADIAL TEMPERATURE GRADIENTS



Internal
Memorandum

APPENDIX G

Bendix Aerospace Systems Division

Ann Arbor, Michigan

Date 10 June 1974 Letter No. LAGEOS-30

To J. Brueger

From E. Granholm

Subject LAGEOS Thermal/Optical Test, Summary of Thermal Analysis Results

Reference: LAGEOS-24, "LAGEOS Thermal/Optical Test, Retroreflector and Mount Thermal Performance", dated 30 May 1974.

This memorandum presents a complete set of retroreflector and mount temperature predictions for the subject test. The results are shown in Table 1 which lists case number, condition, various temperatures, and retroreflector axial and radial temperature differences.

Cases 1 through 6 were previously documented in the referenced memorandum. The +30°C cavity temperature corresponds to a bare machined aluminum retainer ring and satellite exterior surface. The -30°C cavity temperature reflects application of IIT's Z-93 thermal coating on the retainer ring and satellite exterior surfaces.

Cases 7 through 12 were run to determine retroreflector and mount temperature levels which are pecular to the T/V test conditions. As stated above, bare machined aluminum and Z-93 induce high and low satellite cavity temperatures. Therefore from an orbital performance standpoint, the thermal results of cases 7 through 12 are not significant and are for general information purposes.

Case 13 was run to assure that the one sun, no IR radiation environment promotes maximum retroreflector temperature gradients. When a comperison to case 1 is made, both gradients for case 13 are lower. Therefore, the full sun, no IR environment represents the worst case thermal environment.

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TABLE 1

LAGEOS Thermal/Vacuum Test, Retroreflector and Mount Thermal Performance

Case	Condition	Cavity Temp	Retro Face Temp	Lower Kel F Ring Temp	Upper Kel F Ring Temp	Retainer Ring Temp.	Retro ΔT Axial	Retro ΔT Radial
1	Sun, No IR, Bare Al	+30°C	2.8°C	30.1°C	51.1°C	51.3°C	1.9°C	1.3°C
2	Sun, No IR, Z-93	-30°C	-46.9°C	-30.0°C	-26.4°C	-26.3°C	1.0°C	0.4°C
3	No Sun, No IR, Bare Al	+30°C	-20.9°C	29.8°C	12.4°C	12.4°C	1.6°C	1.1°C
4	No Sun, No IR, Z-93	-30°C	-69.0°C	-30.2°C	-48.4°C	-48.9°C	0.7°C	0.5°C
5	IR, No Sun, Bare Al	+30°C	-12.1°C	29.8°C	14.9°C	14.9°C	1.4°C	0.9°C
6	IR, No Sun, Z-93	-30°C	-53.7°C	-30.1°C	-42.3°C	-43.3°C	0.4°C	0.3°C
7	Sun, No IR, Z-93	+30°C	-11.7°C	29.8°C	12.2°C	12.2°C	1.9°C	0.8°C
8	Sun, No IR, Bare Al	-30°C	-34.7°C	-29.8°C	6.9°C	7.2°C	1.0°C	0.6°C
9	No Sun, No IR, Z-93	+30°C	-27.4°C	29.7°C	-6.3°C	-6.4°C	1.6°C	0.9°C
10	No Sun, No IR, Bare Al	-30°C	-65.4°C	-30.1°C	-38.2°C	-38.2°C	0.6°C	0.5°C
11	IR, No Sun, Z-93	+30°C	-17.2°C	29.7°C	-0.8°C	-0.9°C	1.4°C	0.8°C
12	IR, No Sun, Bare Al	-30°C	-51.7°C	-30.1°C	-35.5°C	-35.5°C	0.4°C	0.3°C
13	Sun, IR, Bare Al	+30°C	9.9°C	30.1°C	53.0°C	53.3°C	1.6°C	1.1°C

NOTES:

1. MSFC mounting rings are hard mounted to cavity shoulder.
2. Retroreflector tab/ring mount gap = 0.003 inches.

Internal
Memorandum

Bendix Aerospace Systems Division

Date 27 June 1974 Letter No. LAGEOS-33 Ann Arbor, Michigan

To J. Brueger

From E. Granholm

Subject LAGEOS Thermal/Optical Test, Test Item Temperature Stabilization and FFDI Viewing Time Criteria

Reference: Memo LAGEOS-30, "LAGEOS Thermal Optical Test, Summary of Thermal Analysis Results", dated 10 June 1974

Introduction

A detailed thermal analysis was conducted to determine temperature stabilization and maximum allowable far field diffraction instrument (FFDI) evaluation time criteria for the LAGEOS test item. Most of the thermal/optical test time will be consumed by lengthly temperature stabilization periods which must be defined before an accurate test time line can be generated. Results of the analysis will be used to schedule manpower for test coverage, to procure consumable test materials, and for planning purposes.

Summary

The results of the subject thermal analysis indicate the following:

1. The test item temperature stabilization period after changing the chamber environmental conditions will be four (4) hours.

2. The maximum allowable time for FFDI optical evaluation of the test item will be four (4) minutes.

3. The time necessary for test item temperature re-stabilization after FFDI evaluation will be one (1) hour.

Analysis

The thermal math model used to generate steady-state temperature levels presented in the referenced memorandum was converted to predict the test item temperature response in the thermal/vacuum chamber. The thermal analysis assumptions pertaining to all cases were as follows:

1) The retroreflector and mount configuration was that described in MSFC DWG #50M23161, "Corner Cube Mount Assembly", Rev. A, dated 24 April 1974.

2) The cavity and retainer ring IR emittances were 0.05.

3) The retainer ring solar absorptance was 0.37.

4) A 0.08 mm gap was present between the retroreflector tab and the Kel "F" mounting rings.

5) The chamber temperature and pressure were -185°C and 5 x 10^{-6} torr, respectively.

6) The test item/chamber cryowall view factor was 100%.

Results

To determine the maximum time necessary for temperature stabilization after changing chamber environment conditions, the test item was assumed to be initially at 25°C. The retroreflector cavity structure was then lowered to -30°C in 30 minutes and the test item viewed a cryowall temperature of -185°C. Table 1 presents the resulting retroreflector temperature responses and gradients for the chamber cool-down period. At approximately 200 minutes after the initiation of cool-down, the retroreflector radial and axial temperature gradients have stabilized to the nearest 0.1°C of their final levels of 0.50 and 0.66°C, respectively. At 240 minutes, the rate of temperature change for the retroreflector is within the standard temperature stabilization criterionof 2°C/ hr used in thermal/vacuum testing.

Table 2 shows retroreflector temperature responses and gradients for the interval when the test item is being optically evaluated by the FFDI. The test item is assumed to be stabilized with one sun normal to the retroreflector face and with a cavity temperature of 30°C. At the end of 4.0 minutes of FFDI viewing,the original retroreflector radial and axial temperature gradients of 1.28 and 1.89°C have degraded to 1.09°C (15%) and 1.96°C (4%), respectively. At 8.0 minutes the original axial and radial gradients have degraded to 0.95°C (26%) and 2.07°C (10%) which is felt to be unacceptable.

Test item temperature levels after 4.0 minutes of FFDI viewing were selected as the initial temperatures for the re-stabilization period. At the beginning of re-stabilization, the test item was illuminated with one normal sun and the cavity temperature was maintained at 30°C. Table 3 contains the associated retroreflector temperature response. At 20 minutes from the initiation of re-stabilization, the retroreflector radial and axial temperature gradients are within 0.02°C of their original gradients. At 60 minutes, the retroreflector temperatures are approximately 0.5°C from their steady-state levels.

Conclusions

The LAGEOS thermal/optical test temperature stabilization and FFDI viewing times are contained in the summary section of this memorandum. The durations specified will yield accurate thermal/optical performance data while maintaining the total test time at a minimum.

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TABLE 1

LAGEOS THERMAL/OPTICAL TEST
RETROREFLECTOR TEMPERATURE RESPONSE
CHAMBER COOL DOWN

Time (Min)	T_{Tab} (°C)	T_{Face} (°C)	T_{Apex} (°C)	ΔT_{Radial} (°C)	ΔT_{Axial} (°C)
0	25.00	25.00	25.00	0	0
15	6.12	6.25	8.66	0.13	2.41
30	- 9.37	- 9.07	- 7.15	0.30	1.92
45	-22.17	-22.00	-20.37	0.17	1.63
60	-31.72	-31.70	-30.32	0.02	1.38
75	-38.91	-39.01	-37.80	0.10	1.21
90	-44.38	-44.58	-43.49	0.20	1.09
105	-48.61	-48.88	-47.89	0.27	0.99
120	-51.91	-52.23	-51.31	0.32	0.92
135	-54.51	-54.86	-53.99	0.35	0.87
150	-56.56	-56.95	-56.12	0.39	0.83
165	-58.19	-58.61	-57.81	0.42	0.80
180	-59.50	-59.93	-59.17	0.43	0.76
195	-60.56	-61.00	-60.26	0.44	0.74
210	-61.40	-61.86	-61.13	0.46	0.73
225	-62.08	-62.55	-61.83	0.47	0.72
240	-62.62	-63.10	-62.39	0.48	0.71
255	-63.07	-63.55	-62.85	0.48	0.70
270	-63.42	-63.91	-63.22	0.49	0.69
285	-63.71	-64.21	-63.52	0.50	0.69
300	-63.95	-64.44	-63.76	0.49	0.68
∞	-64.9	-65.4	-64.8	0.50	0.66

TABLE 2

LAGEOS THERMAL/OPTICAL TEST
RETROREFLECTOR TEMPERATURE RESPONSE
FFDI OPTICAL EVALUATION OF TEST ITEM

Time (Min	T_{Tab} (°C)	T_{Face} (°C)	T_{Apex} (°C)	ΔT_{Radial} (°C)	ΔT_{Axial} (°C)
0	4.11	2.83	4.72	1.28	1.89
1	3.83	2.58	4.48	1.25	1.90
2	3.50	2.31	4.23	1.19	1.92
3	3.15	2.01	3.97	1.14	1.96
4	2.78	1.69	3.68	1.09	1.99
5	2.40	1.36	3.37	1.04	2.01
6	2.01	1.00	3.04	1.01	2.04
7	1.62	0.64	2.69	0.98	2.05
8	1.22	0.27	2.34	0.95	2.07
9	0.82	-0.10	1.98	0.92	2.08
10	0.43	-0.48	1.61	0.91	2.09
11	0.03	-0.86	1.23	0.89	2.09
12	-0.37	-1.24	0.85	0.87	2.09
13	-0.76	-1.62	0.47	0.86	2.09
14	-1.15	-2.00	0.09	0.85	2.09
15	-1.53	-2.38	-0.29	0.85	2.09
16	-1.92	-2.76	-0.67	0.84	2.09
17	-2.29	-3.13	-1.04	0.84	2.09
18	-2.67	-3.50	-1.41	0.83	2.09
19	-3.03	-3.86	-1.78	0.83	2.08
20	-3.39	-4.22	-2.15	0.83	2.07

TABLE 3

LAGEOS THERMAL/OPTICAL TEST
RETROREFLECTOR TEMPERATURE RESPONSE
TEMPERATURE RE-STABILIZATION AFTER FFDI VIEWING

Time (Min)	T_{Tab} (°C)	T_{Face} (°C)	T_{Apex} (°C)	ΔT_{Radial} (°C)	ΔT_{Axial} (°C)
0	2.78	1.69	3.68	1.09	1.99
10	2.49	1.26	3.18	1.23	1.92
20	2.70	1.41	3.28	1.29	1.87
30	2.99	1.68	3.54	1.31	1.86
40	3.25	1.94	3.81	1.31	1.87
50	3.46	2.16	4.03	1.30	1.87
60	3.63	2.33	4.21	1.30	1.88
70	3.76	2.46	4.34	1.30	1.88
80	3.86	2.56	4.45	1.30	1.89
90	3.94	2.64	4.53	1.30	1.89
100	3.99	2.70	4.59	1.29	1.89
110	4.04	2.74	4.63	1.30	1.89
120	4.07	2.78	4.67	1.29	1.89
∞	4.11	2.83	4.72	1.28	1.89

Memorandum

Aerospace
Systems Division
Ann Arbor, Michigan

Date 28 June 1974 Letter No. LAGEOS-34

To J. Brueger

From E. Granholm

Subject Thermal Analysis of LAGEOS Satellite

Introduction

The LAGEOS Satellite has been thermally modeled in detail and the resulting temperature predictions are presented. The thermal design objective is to minimize the individual retroreflector radial and axial temperature gradients which will optimize the satellite optical performance. Toward this objective the retroreflectors are conductively and radiatively isolated from their mounting cavities. The satellite and retainer ring exterior surfaces were assumed to be bare, machined aluminum ($\alpha s/\epsilon ir$ = 0.37/0.05) to promote upper-bound retroreflector temperature gradients. Ideally, reflective thermal control coatings possessing low solar absorptances and high IR emittances should be applied to the satellite exterior surfaces.

Summary

Based on a 60 cm diameter, bare machined aluminum satellite containing 426 retroreflectors, the core stabilization temperature is approximately 50^{o}C. For a non-spinning satellite in an entirely sun lit orbit the maximum temperature gradient across the aluminum structure is 10^{o}C. The retroreflector temperatures range from -12^{o}C to 20^{o}C depending upon location on the satellite with respect to the sun. The average retroreflector radial and axial temperature gradients are 1.3 and 2.1^{o}C, respectively.

Analysis

The orbit environment imposed on LAGEOS was intented to promote maximum satellite temperatures which induce upper-bound retro-reflector temperature gradients. Orbital characteristics and parameters (contained in the MSFC documents TMX-64627 and S&E-ASTN-PF-72-67) used in the analysis are listed below:

Orbit type: Fully sunlit (hot)
Orbit altitude: 5900 km
Orbit eccentricity: $\leq$ 0.01

Satellite attitude: No preferred orientation
Satellite spin rate: No spin
Solar constant: 1415.5 w/m^2
Albedo reflectance: 30%
Earth IR emission: 237 w/m^2

The following assumptions were made for the purpose of thermal analysis:

1.0 The configuration of the retroreflector mount assembly was a described by MSFC Dwg. #50M23161, "Corner Cube Mount Assembly", Rev. A, dated 24 April 1974. Details of the mount are shown in Figure 1.

2.0 The satellite exterior surface was bare, machined aluminum ($\alpha s/\epsilon ir$ = 0.37/0.05).

3.0 The satellite had a diameter of 60 cm and contained 426 circular faced retroreflectors.

4.0 The satellite terminator was coincident with the mounting interface between the sphere halves.

5.0 Thermal/physical properties of the retroreflector are identical to those previously presented in the first program review.

6.0 The retroreflector face was assumed to be recessed 1.0 mm below the retainer ring exterior surface.

The satellite model consisted of 158 nodes and 498 conduction and radiation resistors. Four retroreflectors at various locations on the satellite were analyzed in detail. The locations selected were 1) normal to the sun, 2) at 45° off-sun 3) on the satellite shadowed side, and 4) on the satellite terminator.

Results

For the previously stated orbital conditions and thermal/math model assumptions the satellite stabilization temperature is 50°C. For a non-spinning satellite the hot side and cold side temperatures are 55°C and 45°C respectively. The total satellite core temperature fluctuation during the orbit duration is within 0.1°C.

Table 1 presents radial and axial temperature gradients at various orbital times for the four retroreflectors analyzed in detail. The maximum retroreflector axial and radial temperature gradients are 2.4 and 1.6°C, respectively for the retroreflector normal to the sun (retroreflector #1). The average axial and radial temperature gradients for the retroreflectors analyzed are 2.1 and 1.3°C, respectively. The average retroreflector temperature is 3°C.

Conclusions

Itek was previously supplied retroreflector temperature gradients in memo LAGEOS-23 on 28 May 1974 to permit analytical determination of optical performance. The retroreflector gradients corresponded to a bare machined aluminum satellite in a fully sunlit orbit. A comparison of the previously transmitted data and the results of the satellite thermal analysis are presented below:

Item	Itek Analysis Inputs (27 May 1974)	Satellite Thermal Analysis (24 June 1974)
Corner Temperature	2.8°C	3.0°C
ΔT radial	1.3°C	1.3°C
ΔT axial	1.9°C	2.1°C

As seen by the above, there is a good correlation between the Itek optical analysis inputs and the satellite orbital thermal analysis levels. Therefore, there is a high degree of confidence that optical performance based upon previously supplied thermal analysis inputs will be representative of the actual LAGEOS satellite optical performance.

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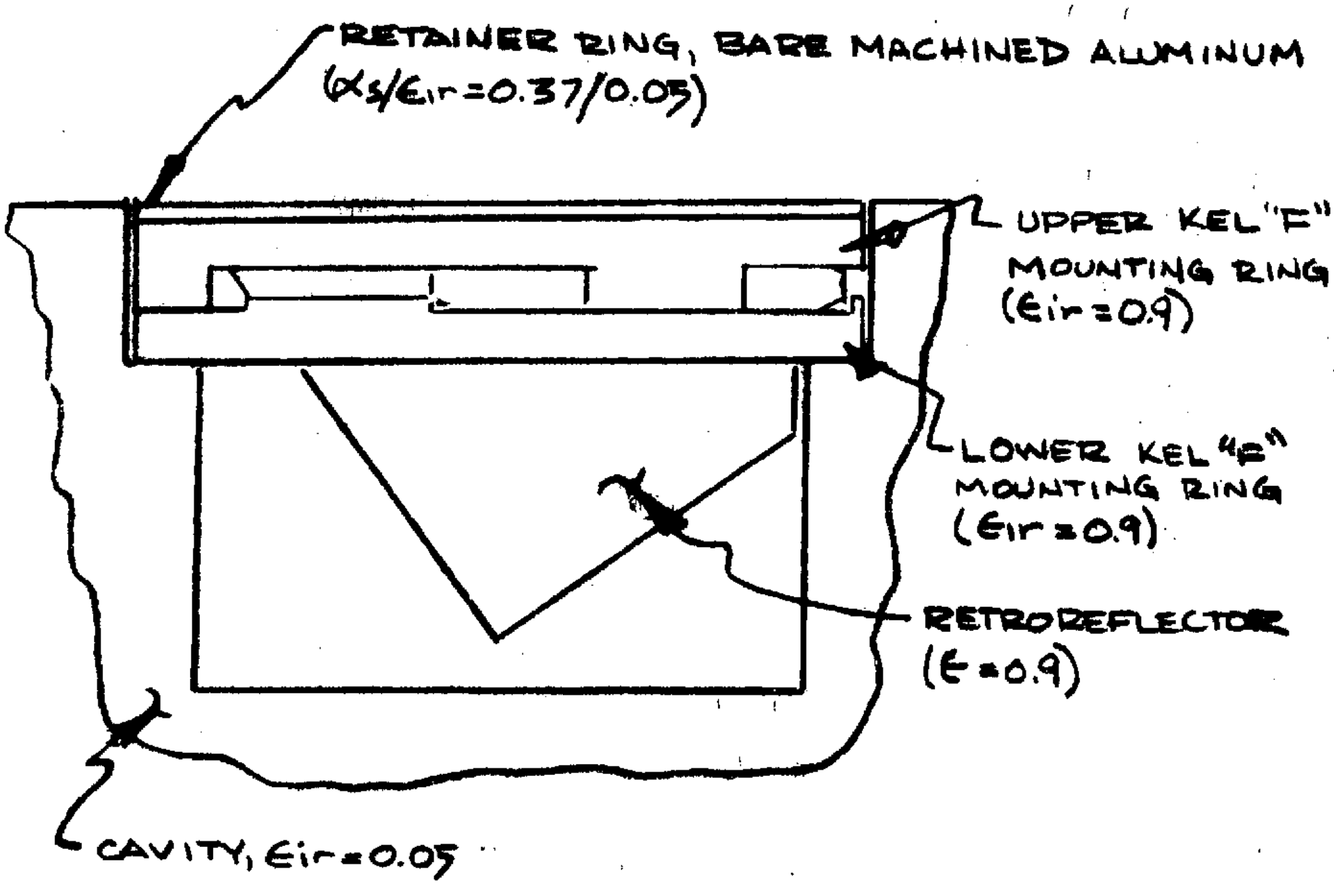
FIGURE 1

RETROREFLECTOR AND MOUNT ASSEMBLY

MSFC DWG NO 50M23161



NOTES:

1. RING ASSEMBLY IS HARD MOUNTED TO CAVITY SHOLDER WITH 3/#2-56 SCREWS.

2. GAP OF 0.08 MM BETWEEN RETROREFLECTOR TAB AND UPPER KEL "F" RING.

3. RETROREFLECTOR TAB RESTS ON LOWER KEL "F" RING.

TABLE 1 - LAGEOS SATELLITE THERMAL ANALYSIS
RETROREFLECTOR THERMAL PERFORMANCE

Orbital Time (Min)	Retro #1		Retro #2		Retro #3		Retro #4	
	ΔT_r (°C)	ΔT_a (°C)	ΔT_r (°C)	ΔT_a (°C)	ΔT_r (°C)	ΔT_a (°C)	ΔT_r (°C)	ΔT_a (°C)
0	1.53	2.39	1.30	1.96	1.14	1.84	1.10	2.00
50	1.56	2.43	1.31	2.16	1.14	1.78	1.15	1.99
100	1.58	2.41	1.36	2.18	1.13	1.88	1.19	1.97
150	1.57	2.35	1.37	2.13	1.15	1.96	1.17	1.69
200	1.56	2.41	1.36	2.03	1.17	1.94	1.12	1.87
225	1.58	2.47	1.34	2.04	1.18	1.92	1.14	2.08
Average	1.6	2.4	1.3	2.1	1.2	1.9	1.1	1.9
Retro Temp (Ave over orbit)	20°C		9°C		-12°C		-6°C	

NOTE:

1. For the four retroreflectors analyzed the average radial and axial temperature gradients are 1.3 and 2.1°C, respectively.

2. The average retroreflector temperature over the orbit duration is 3°C.

3. Retro #1 : Normal to sun
   Retro #2 : 45° off-sun
   Retro #3 : Shadowed side off Satellite, 180° off-sun
   Retro #4 : Satellite Terminator, 90° off-sun

Internal
Memorandum

APPENDIX K

Bendix Aerospace Systems Division

Ann Arbor, Michigan

Date 10 September 1974 Letter No. LAGEOS-41

To J. Brueger (w/enclosure)

From E. Granholm

Subject Final Thermal Design/Analysis of LAGEOS Satellite

Enclosure: LAGEOS, Final Satellite Thermal/Mathematical Model and Thermal Model Results

Introduction

The LAGEOS Satellite has been thermally modeled and the associated network and temperature predictions are contained in the Enclosure. Pages 1-17 specify thermal capacitance, conduction and radiation resistance, and orbital heating information. Detailed satellite/retroreflector temperature responses are given on pages 18-34.

The satellite thermal design objective is to minimize individual retroreflector radial and axial temperature gradients which will optimize optical performance. Toward this objective the retroreflectors are conductively and radiatively isolated from their mounting cavities. The satellite interior/exterior and retainer ring surfaces were assumed to be bare, machined 6061-T6 aluminum having thermal optical properties of $\alpha_s/\epsilon_{ir} = 0.15/0.05$ which were correlated with test data.

Summary and Recommendations

Based on a 60 cm diameter, bare machined aluminum satellite containing 426 retroreflectors, the core stabilization temperature is approximately 55°C. For a non-spinning satellite in an entirely sun lit orbit the maximum temperature gradient across the aluminum structure is 8°C. The retroreflector temperatures range from -8°C to 16°C depending upon location on the satellite with respect to the sun. The average retroreflector radial and axial temperature gradients are 1.4 and 2.3°C, respectively.

It was originally felt that LAGEOS optical performance would be sensitive to thermal control coatings applied to the satellite and retroreflector retainer ring exterior surfaces. However, after thermal/optical testing the retroreflectors performed satisfactorily for cavity temperatures ranging from -30 to +60°C.

Therefore, the following LAGEOS thermal design recommendations are made:

1. The retroreflector mounting cavity should possess a low (less than 5%) infrared emittance.

2. The retroreflector mounting rings should have a low thermal conductivity and should provide minimal or no contact with the retroreflector mounting tabs.

3. Thermal coatings/finishes which are applied to the satellite exterior should be of low solqr absorptance (high visible reflectance) to permit tracking by ground stations.

4. No particular level of satellite external surface IR emittance is recommended since it appears to have little effect on retroreflector optical performance.

Analysis

The orbit environment imposed on LAGEOS was intented to promote maximum satellite temperatures which induce upper-bound retroreflector temperature gradients. Orbital characteristics and parameters (contained in the MSFC documents TMX-64627 and S&E-ASTN-PF-72-67) used in the analysis are listed in Table 1. In addition the following orbital heating constaints were used in the thermal analysis.

Solar constant: 1415.5 w/m^2
Albedo reflectance: 30%
Earth IR Emission: 237 w/m^2

The satellite thermal model as shown in Figure 1 consisted of 158 nodes and 483 conduction and radiation resistors. Four retroreflectors at various locations on the satellite were analyzed in detail. The locations were 1) normal to the sun, 2) at 45° off-sun, 3) at 180° off-sun, and 4) at 90° off-sun.

C-3

TABLE 1

LAGEOS

SATELLITE THERMAL ANALYSIS ASSUMPTIONS*

ORBIT PARAMETERS

ALTITUDE = 5900 KM
EQUATORIAL INCLINATION = 110°
ECCENTRICITY $\leq$ 0.01
FULL SUNLIT ORBIT (NO ECLIPSE)

SATELLITE ATTITUDE

SPIN RATE = 0
SATELLITE EQUATOR PLANE PERPENDICULAR TO ECLIPTIC
SATELLITE EQUATOR AND TERMINATOR ARE COINCIDENT

SATELLITE THERMAL/OPTICAL PROPERTIES

EXTERIOR SURFACES (SATELLITE STRUCTURE AND RETAINER RINGS)
$\alpha s/\epsilon ir$ = 0.15/0.05 (BARE MACHINED 6061-T6 ALUMINUM)

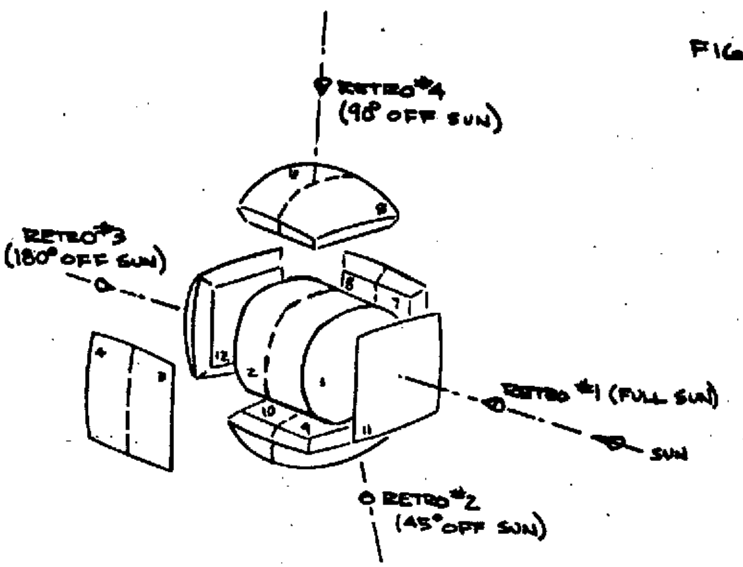
INTERIOR SURFACES
ϵir = 0.05 (BARE MACHINED 6061-T6 ALUMINUM)

*SATELLITE THERMAL ANALYSIS INCLUDES CORRELATED PROPERTIES OF RETROREFLECTOR VOLUMETRIC SOLAR ABSORPTANCE AND SATELLITE SOLAR ABSORPTANCE.

LAGEOS

SATELLITE THERMAL/MATHEMATICAL MODEL

FIGURE - 1



TOTAL NUMBER OF RETROREFLECTORS = 426
DIAMETER OF SATELLITE = 60.0 CM
TOTAL WEIGHT = 385 KG

LAGEOS

DESCRIPTION OF SATELLITE THERMAL/MATH MODEL

ITEM	NODE IDENTIFICATION	NUMBER OF NODES
BALANCE WEIGHT (30M20456)	1, 2	2
HALF SPHERE (30M20459)	3-12	10
INDIVIDUAL RETROREFLECTORS (50M24461)	25-42 RETRO #1, FULL SUN 50-67 RETRO #2, 45° OFF SUN 75-92 RETRO #3, 180° OFF SUN 100-117 RETRO #4, 90° OFF SUN	18 PER RETRO 72 TOTAL
INDIVIDUAL RETAINER RINGS (50M23170)	43 RETRO #1 68 RETRO #2 93 RETRO #3 118 RETRO #4	4
INDIVIDUAL KEL F RINGS, UPPER & LOWER (50M24459, P/N 1 & 2)	44-49 RETRO #1 69-74 RETRO #2 94-99 RETRO #3 119-124 RETRO #4	6 PER RETRO 24 TOTAL
COMBINED RETROS, KEL F RINGS, RETAINER RINGS	125-164	40
SPACE	201-206	6
TOTAL NODES	-	158

TOTAL NUMBER OF RADIATION AND CONDUCTION RESISTORS = 483

The following are satellite nodes of particular interest:

Node	Description
25	Tab, Retro 1
31	Face, Retro 1
42	Apex, Retro 1
50	Tab, Retro 2
56	Face, Retro 2
67	Apex, Retro 2
75	Tab, Retro 3
81	Face, Retro 3
92	Apex, Retro 3
100	Tab, Retro 4
106	Face, Retro 4
117	Apex, Retro 4

Results

For the previously stated orbital conditions and thermal/math model assumptions the satellite stabilization temperature is 55°C as shown by Figure 2. For a non-spinning satellite the hot side and cold side temperatures are 60°C and 52°C respectively. The total satellite core temperature fluctuation during the orbit duration is within 0.1°C.

Figure 3 shows that the maximum and minimum retroreflector face temperatures are 16 and -8°C, respectively for the sun side and dark retroreflectors. At any one time all retroreflectors will be within 24°C of one another. The maximum temperature fluctuation of 5°C is experienced by the retroreflector located on the satellite top surface.

Temperature profiles for the sun-side retroreflector are presented in Figure 4. There is an approximate 47°C temperature drop between the cavity and the corner face. Axial and radial temperature gradients are 2.5 and 1.7°C, respectively.

Thermal performance for the retroreflector located on the satellite shadowed side is shown in Figure 4. There is an approximate 60°C temperature drop between the cavity and the corner face. Temperature gradients in the axial and radial directions are 2.1 and 1.3°C respectively. As shown by both Figures 4 and 5 corner temperature gradients are nearly constant throughout the orbit.

FIGURE 2
SATELLITE STRUCTURE STABILIZATION TEMPERATURES

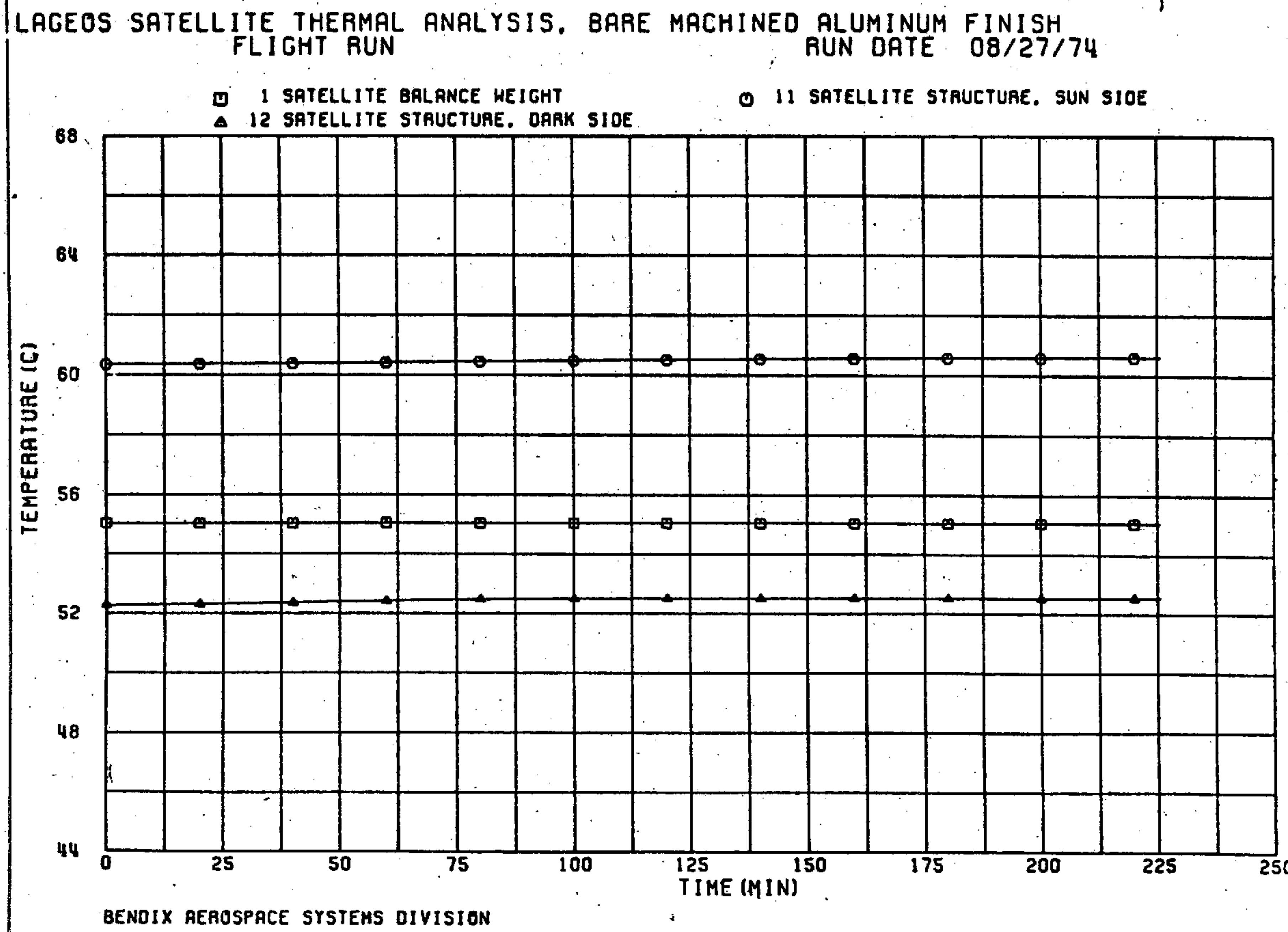


FIGURE 3
TYPICAL RETROREFLECTOR TEMPERATURE RESPONSES

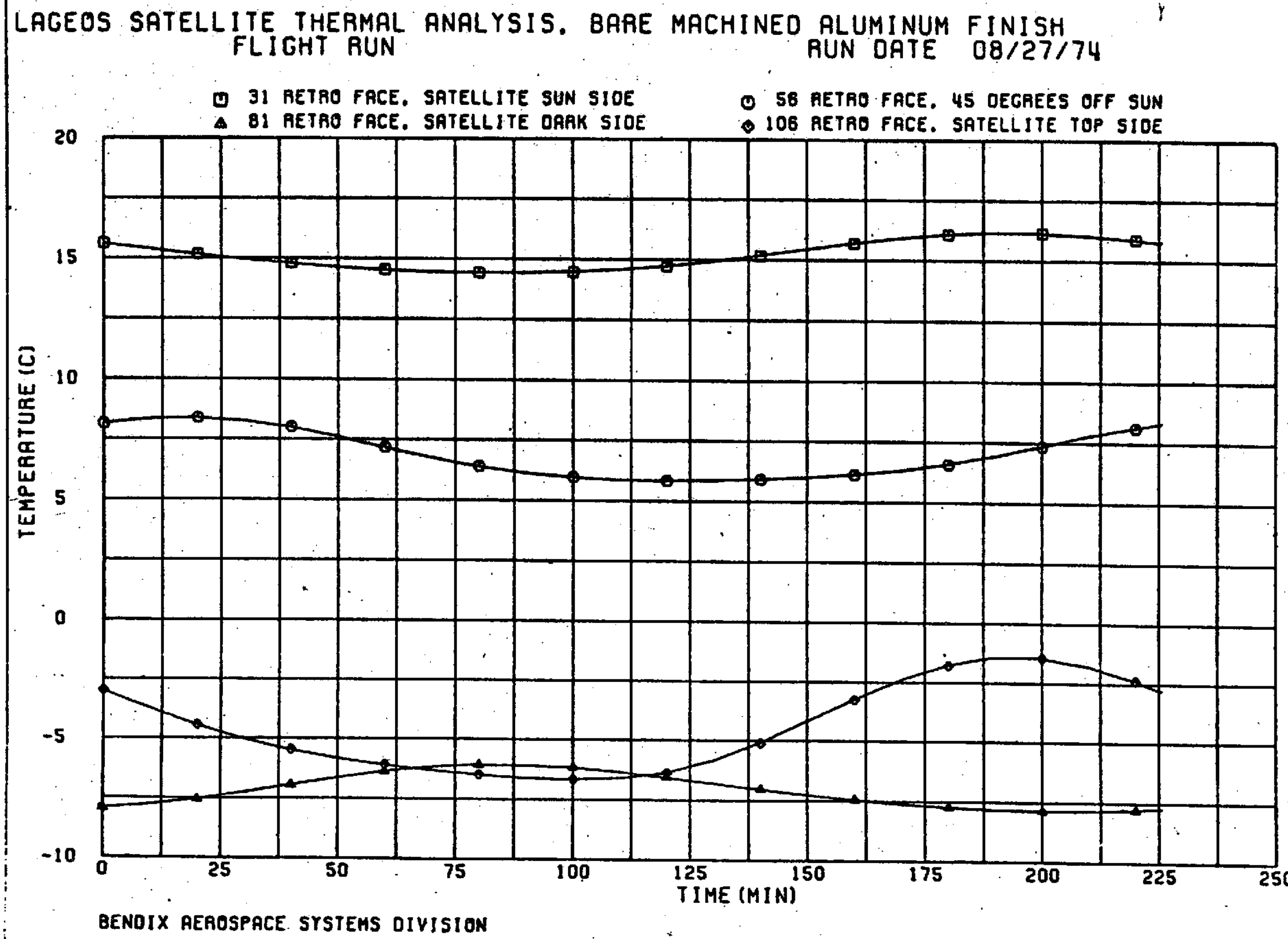


FIGURE 4
RETROREFLECTOR TEMPERATURE DISTRIBUTIONS,
SATELLITE SUN SIDE

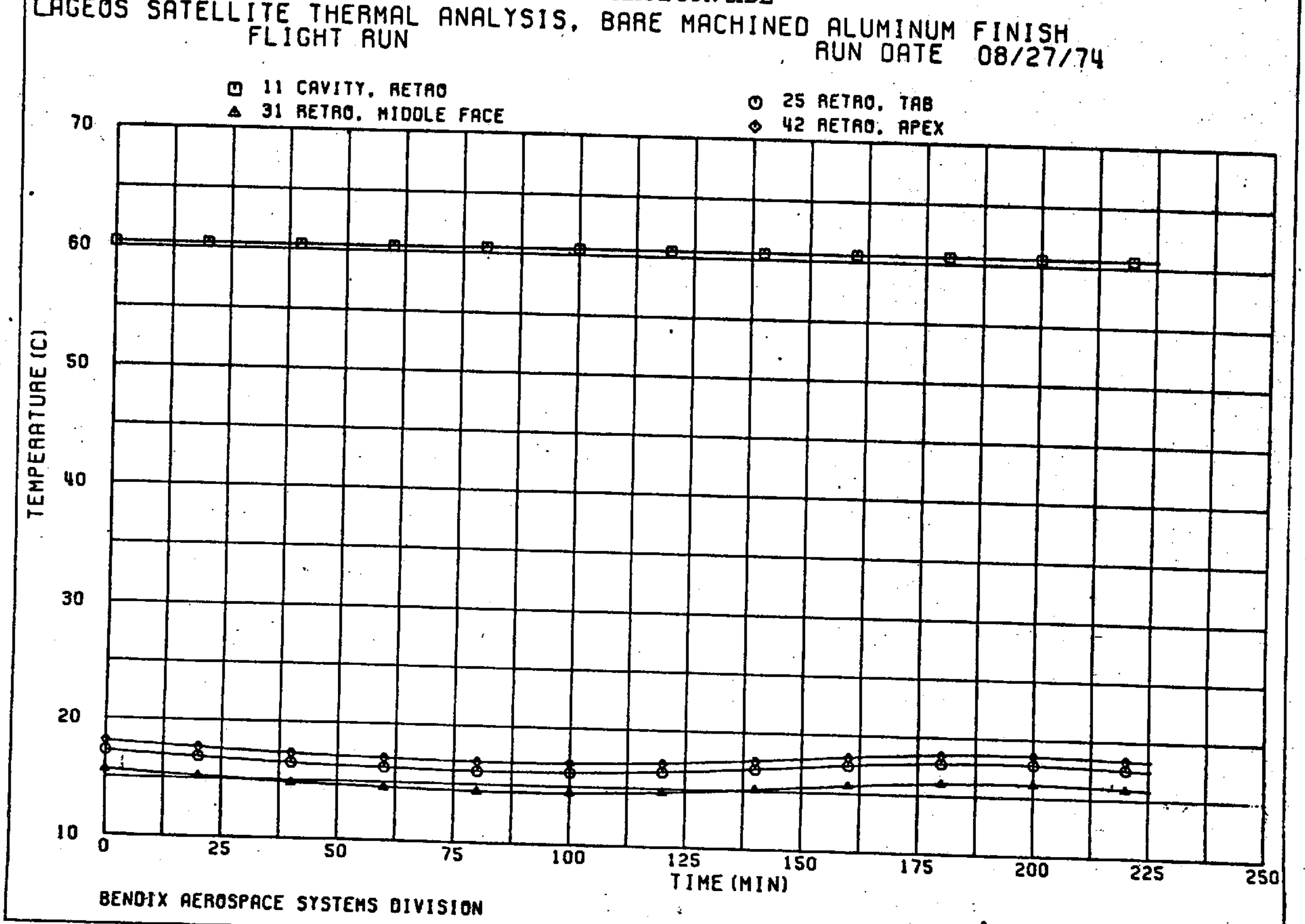


FIGURE 5

RETROREFLECTOR TEMPERATURE DISTRIBUTIONS, SATELLITE DARK SIDE

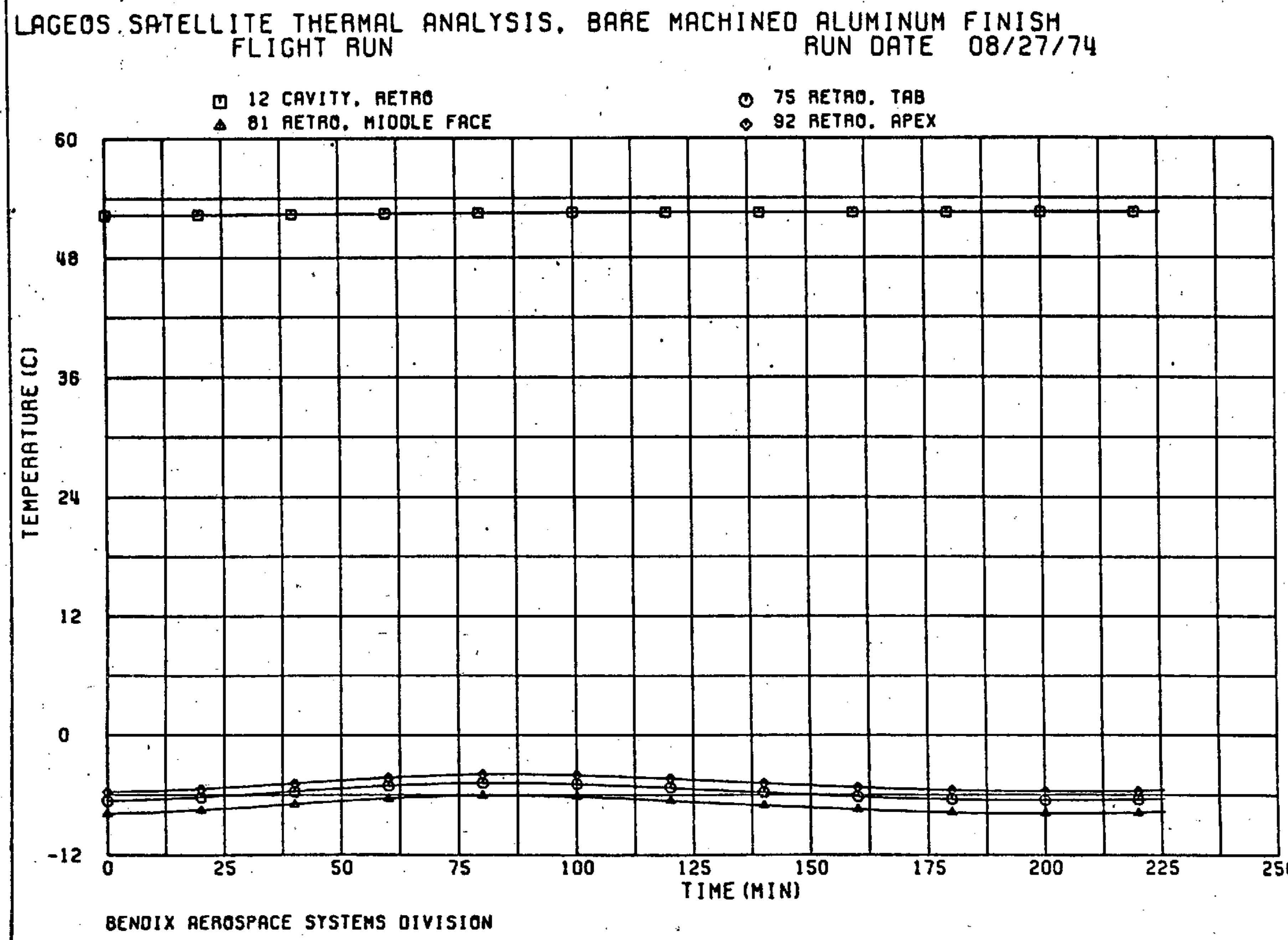


Table 2 presents axial and radial temperature gradients for the four-retroreflectors analyzed in detail. The maximum retroreflector axial and radial temperature gradients are 2.5 and 1.7°C, respectively for the retroreflector normal to the sun (retroreflector #1). The average axial and radial temperature gradients for the retroreflectors analyzed are 2.3 and 1.4°C, respectively. The average retroreflector temperature is 3.6°C.

Conclusions

Itek was previously supplied retroreflector temperature gradients in memo LAGEOS-23 on 28 May 1974 to permit analytical determination of optical performance. The retroreflector gradients corresponded to a bare machined aluminum satellite in a fully sunlit orbit. A close comparison of the previously transmitted data and the results of the satellite thermal analysis are presented below:

Item	Itek Analysis Inputs (27 May 1974)	Satellite Thermal Analysis (27 August 1974)
Corner Temperature	2.8°C	3.6°C
ΔT radial	1.3°C	1.4°C
ΔT axial	1.9°C	2.3°C

Based on the 27 May 1974 thermal inputs supplied by Bendix, Itek predicted that the retroreflector optical return in the 32 to 41 μ rad annulus would be 16.9%. When compared to the corresponding isothermal return of 17.7%, an optical degradation of 5% is apparent.

Optical testing conducted at +60°C cavity temperature indicated an optical return of 13.5% versus 12.4% for an isothermal retroreflector. The improvement of approximately 9% in optical performance could be realized for the LAGEOS satellite since its core temperature of 55°C is nearly the same as the test level.

From the above analysis and test results, the retroreflector degradation due to thermal perturbation is less than the maximum allowable level of 50%. Therefore, there is a high degree of confidence that the LAGEOS will perform adequately during its intended mission.

E. Granholm
E. Granholm

EG:b
cc: S. Krajewski (w/o enclosure), L. Lewis (w/o enclosure)
J. Maszatics (w/o enclosure), J. Monroe (w/o enclosure)
J. McNaughton (w/enclosure)
MSFC-W. Johnson, R. Creel (w/enclosures)

TABLE 2

LAGEOS

SUMMARY OF SATELLITE FLIGHT THERMAL ANALYSIS RESULTS*

LOCATION	RETRO #1 FULL SUN	RETRO #2 45° OFF SUN	RETRO #3 180° OFF SUN	RETRO #4 90° OFF SUN	AVERAGE
RETRO TEMPERATURE	16.0°C	8.5°C	-7.5°C	-2.5°C	3.6°C
ΔT AXIAL	2.5°C	2.2°C	2.1°C	2.3°C	2.3°C
ΔT RADIAL	1.7°C	1.5°C	1.3°C	1.2°C	1.4°C

NOTE: 1. SATELLITE CORE TEMPERATURE = 54.0°C.

2. APPROXIMATE 8°C GRADIENT ACROSS SATELLITE STRUCTURE.

*BARE MACHINED 6061-T6 ALUMINUM SATELLITE AND RETAINER RINGS.

ENCLOSURE

LAGEOS, Final Satellite Thermal/Mathematical Model and Thermal Model Results

10 September 1974

Pages 1 - 17 . . . . . . LAGEOS Satellite Thermal/Mathematical Model Description

Pages 17 - 34 . . . . . LAGEOS Satellite Orbital Temperature Profiles

BENDIX AEROSPACE SYSTEMS DIVISION

THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN
RUN NUMBER
RUN DATE 08/27/74
RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

EQUILIBRIUM TOLERANCE = 0.0500 DEGREES F

NODE NUMBER

TABLE NUMBER

NODAL DATA

0	0		0	0			
1	1	0	0.1660E 02	0.1310E 03	0	0	0.0
2	1	0	0.1650E 02	0.1310E 03	0	0	0.0
3	0	0	0.8600E 01	0.1300E 03	2	0	0.1000E 01
4	0	0	0.8600E 01	0.1290E 03	2	0	0.1000E 01
5	0	0	0.8600E 01	0.1300E 03	6	0	0.1000E 01
6	0	0	0.8600E 01	0.1290E 03	6	0	0.1000E 01
7	0	0	0.8600E 01	0.1300E 03	4	0	0.1000E 01
8	0	0	0.8600E 01	0.1290E 03	4	0	0.1000E 01
9	0	0	0.8600E 01	0.1300E 03	5	0	0.1000E 01
10	0	0	0.8600E 01	0.1290E 03	5	0	0.1000E 01
11	0	0	0.1720E 02	0.1410E 03	1	0	0.1000E 01
12	0	0	0.1720E 02	0.1270E 03	3	0	0.1000E 01
25	0	0	0.1060E-02	0.6350E 02	7	0	0.1950E 00
26	0	0	0.1060E-02	0.6350E 02	7	0	0.1950E 00
27	0	0	0.1050E-02	0.6350E 02	7	0	0.1950E 00
28	0	0	0.5360E-03	0.6080E 02	7	0	0.1030E 00
29	0	0	0.5360E-03	0.6080E 02	7	0	0.1030E 00
30	0	0	0.5360E-03	0.6080E 02	7	0	0.1030E 00
31	0	0	0.5880E-03	0.6040E 02	7	0	0.1030E 00
32	0	0	0.5600E-03	0.6390E 02	11	0	0.5440E-01
33	0	0	0.5600E-03	0.6390E 02	11	0	0.5440E-01
34	0	0	0.5600E-03	0.6390E 02	11	0	0.5440E-01
35	0	0	0.4050E-03	0.6300E 02	11	0	0.3930E-01
36	0	0	0.4050E-03	0.6300E 02	11	0	0.3930E-01
37	0	0	0.4050E-03	0.6300E 02	11	0	0.3930E-01
38	0	0	0.5430E-03	0.6300E 02	11	0	0.5270E-01
39	0	0	0.4300E-03	0.6400E 02	11	0	0.4170E-01
40	0	0	0.4300E-03	0.6400E 02	11	0	0.4170E-01
41	0	0	0.4300E-03	0.6400E 02	11	0	0.4170E-01
42	0	0	0.1860E-03	0.6500E 02	11	0	0.1800E-01
43	0	0	0.7960E-03	0.1520E 03	1	0	0.2030E-02
44	0	0	0.7500E-03	0.1510E 03	0	0	0.0
45	0	0	0.7500E-03	0.1510E 03	0	0	0.0
46	0	0	0.7500E-03	0.1510E 03	0	0	0.0
47	0	0	0.5630E-03	0.1410E 03	0	0	0.0
48	0	0	0.5630E-03	0.1410E 03	0	0	0.0
49	0	0	0.5630E-03	0.1410E 03	0	0	0.0
50	0	0	0.1060E-02	0.4960E 02	8	0	0.1950E 00

INITIAL TEMPERATURE (°F)

TABLE MULTIPLICATION FACTOR

INDEPENDENT VARIABLE IS TIME

THERMAL CAPACITANCE (BTU/°F)

NODAL DATA (CONTINUED)

51	0	0	0.1060E-02	0.4960E 02	8	0	0.1950E 00
52	0	0	0.1060E-02	0.4960E 02	8	0	0.1950E 00
53	0	0	0.5360E-03	0.4730E 02	8	0	0.1030E 00
54	0	0	0.5360E-03	0.4730E 02	8	0	0.1030E 00
55	0	0	0.5360E-03	0.4730E 02	8	0	0.1030E 00
56	0	0	0.5880E-03	0.4690E 02	8	0	0.1030E 00
57	0	0	0.5600E-03	0.4990E 02	11	0	0.3850E-01
58	0	0	0.5600E-03	0.4990E 02	11	0	0.3850E-01
59	0	0	0.5600E-03	0.4990E 02	11	0	0.3850E-01
60	0	0	0.4050E-03	0.4910E 02	11	0	0.2780E-01
61	0	0	0.4050E-03	0.4910E 02	11	0	0.2780E-01
62	0	0	0.4050E-03	0.4910E 02	11	0	0.2780E-01
63	0	0	0.5430E-03	0.4910E 02	11	0	0.3730E-01
64	0	0	0.4300E-03	0.5000E 02	11	0	0.2950E-01
65	0	0	0.4300E-03	0.5000E 02	11	0	0.2950E-01
66	0	0	0.4300E-03	0.5000E 02	11	0	0.2950E-01
67	0	0	0.1850E-03	0.5080E 02	11	0	0.1270E-01
68	0	0	0.7960E-03	0.1290E 03	1	0	0.1440E-02
69	0	0	0.7500E-03	0.1290E 03	0	0	0.0
70	0	0	0.7500E-03	0.1290E 03	0	0	0.0
71	0	0	0.7500E-03	0.1290E 03	0	0	0.0
72	0	0	0.5630E-03	0.1300E 03	0	0	0.0
73	0	0	0.5630E-03	0.1300E 03	0	0	0.0
74	0	0	0.5630E-03	0.1300E 03	0	0	0.0
75	0	0	0.1060E-02	0.2040E 02	9	0	0.1950E 00
76	0	0	0.1060E-02	0.2040E 02	9	0	0.1950E 00
77	0	0	0.1060E-02	0.2040E 02	9	0	0.1950E 00
78	0	0	0.5360E-03	0.1840E 02	9	0	0.1030E 00
79	0	0	0.5360E-03	0.1840E 02	9	0	0.1030E 00
80	0	0	0.5360E-03	0.1840E 02	9	0	0.1030E 00
81	0	0	0.5880E-03	0.1810E 02	9	0	0.1030E 00
82	0	0	0.5600E-03	0.2080E 02	0	0	0.0
83	0	0	0.5600E-03	0.2080E 02	0	0	0.0
84	0	0	0.5600E-03	0.2080E 02	0	0	0.0
85	0	0	0.4050E-03	0.2010E 02	0	0	0.0
86	0	0	0.4050E-03	0.2010E 02	0	0	0.0
87	0	0	0.4050E-03	0.2010E 02	0	0	0.0
88	0	0	0.5430E-03	0.2000E 02	0	0	0.0
89	0	0	0.4300E-03	0.2100E 02	0	0	0.0
90	0	0	0.4300E-03	0.2100E 02	0	0	0.0
91	0	0	0.4300E-03	0.2100E 02	0	0	0.0
92	0	0	0.1860E-03	0.2190E 02	0	0	0.0
93	0	0	0.7960E-03	0.8540E 02	18	0	0.1000E 01
94	0	0	0.7500E-03	0.8540E 02	0	0	0.0
95	0	0	0.7500E-03	0.8540E 02	0	0	0.0
96	0	0	0.7500E-03	0.8540E 02	0	0	0.0
97	0	0	0.5630E-03	0.1260E 03	0	0	0.0
98	0	0	0.5630E-03	0.1260E 03	0	0	0.0
99	0	0	0.5630E-03	0.1260E 03	0	0	0.0
100	0	0	0.1060E-02	0.2920E 02	10	0	0.1950E 00
101	0	0	0.1060E-02	0.2920E 02	10	0	0.1950E 00

NODAL DATA (CONTINUED)

102	0	0	0.1060E-02	0.2920E 02	10	0	0.1950E 00
103	0	0	0.5360E-03	0.2730E 02	10	0	0.1030E 00
104	0	0	0.5360E-03	0.2730E 02	10	0	0.1030E 00
105	0	0	0.5360E-03	0.2730E 02	10	0	0.1030E 00
106	0	0	0.5880E-03	0.2700E 02	10	0	0.1030E 00
107	0	0	0.5600E-03	0.2980E 02	0	0	0.0
108	0	0	0.5600E-03	0.2980E 02	0	0	0.0
109	0	0	0.5600E-03	0.2980E 02	0	0	0.0
110	0	0	0.4050E-03	0.2920E 02	0	0	0.0
111	0	0	0.4050E-03	0.2920E 02	0	0	0.0
112	0	0	0.4050E-03	0.2920E 02	0	0	0.0
113	0	0	0.5430E-03	0.2910E 02	0	0	0.0
114	0	0	0.4300E-03	0.3010E 02	0	0	0.0
115	0	0	0.4300E-03	0.3010E 02	0	0	0.0
116	0	0	0.4300E-03	0.3010E 02	0	0	0.0
117	0	0	0.1860E-03	0.3110E 02	0	0	0.0
118	0	0	0.7960E-03	0.9020E 02	19	0	0.1000E 01
119	0	0	0.7500E-03	0.9020E 02	0	0	0.0
120	0	0	0.7500E-03	0.9020E 02	0	0	0.0
121	0	0	0.7500E-03	0.9020E 02	0	0	0.0
122	0	0	0.5630E-03	0.1290E 03	0	0	0.0
123	0	0	0.5630E-03	0.1290E 03	0	0	0.0
124	0	0	0.5630E-03	0.1290E 03	0	0	0.0
125	0	0	0.7200E 00	0.6300E 02	12	0	0.1000E 01
126	0	0	0.3550E 00	0.2990E 02	13	0	0.9720E 00
127	0	0	0.3650E 00	0.2920E 02	13	0	0.1000E 01
128	0	0	0.7200E 00	0.2010E 02	14	0	0.1000E 01
129	0	0	0.3650E 00	0.2350E 02	15	0	0.1000E 01
130	0	0	0.3650E 00	0.2280E 02	15	0	0.1000E 01
131	0	0	0.3650E 00	0.2220E 02	16	0	0.1000E 01
132	0	0	0.3650E 00	0.2150E 02	16	0	0.1000E 01
133	0	0	0.3550E 00	0.2890E 02	17	0	0.9720E 00
134	0	0	0.3650E 00	0.2830E 02	17	0	0.1000E 01
135	0	0	0.5570E-01	0.1520E 03	1	0	0.1420E 00
136	0	0	0.2750E-01	0.8990E 02	20	0	0.9720E 00
137	0	0	0.2830E-01	0.8910E 02	20	0	0.1000E 01
138	0	0	0.5570E-01	0.8540E 02	18	0	0.7000E 02
139	0	0	0.2830E-01	0.8830E 02	21	0	0.1000E 01
140	0	0	0.2830E-01	0.8760E 02	21	0	0.1000E 01
141	0	0	0.2830E-01	0.8780E 02	22	0	0.1000E 01
142	0	0	0.2830E-01	0.8700E 02	22	0	0.1000E 01
143	0	0	0.2750E-01	0.9010E 02	19	0	0.3450E 02
144	0	0	0.2830E-01	0.8930E 02	19	0	0.3550E 02
145	0	0	0.1580E 00	0.1510E 03	0	0	0.0
146	0	0	0.7760E-01	0.3990E 02	0	0	0.0
147	0	0	0.7990E-01	0.8910E 02	0	0	0.0
148	0	0	0.1580E 00	0.8540E 02	0	0	0.0
149	0	0	0.7990E-01	0.8830E 02	0	0	0.0
150	0	0	0.7990E-01	0.8760E 02	0	0	0.0
151	0	0	0.7990E-01	0.8780E 02	0	0	0.0
152	0	0	0.7990E-01	0.8710E 02	0	0	0.0

NODAL DATA (CONTINUED)

153	0	0	0.7760E-01	0.9020E 02	0	0	0.0
154	0	0	0.7990E-01	0.8940E 02	0	0	0.0
155	0	0	0.1180E 00	0.1410E 03	0	0	0.0
156	0	0	0.5830E-01	0.1290E 03	0	0	0.0
157	0	0	0.6000E-01	0.1290E 03	0	0	0.0
158	0	0	0.1180E 00	0.1260E 03	0	0	0.0
159	0	0	0.6000E-01	0.1290E 03	0	0	0.0
160	0	0	0.6000E-01	0.1280E 03	0	0	0.0
161	0	0	0.6000E-01	0.1290E 03	0	0	0.0
162	0	0	0.6000E-01	0.1280E 03	0	0	0.0
163	0	0	0.5830E-01	0.1290E 03	0	0	0.0
164	0	0	0.6000E-01	0.1280E 03	0	0	0.0
201	0	0	-0.1000E 01	-0.4600E 03	0	0	0.0
202	0	0	-0.1000E 01	-0.4600E 03	0	0	0.0
203	0	0	-0.1000E 01	-0.4600E 03	0	0	0.0
204	0	0	-0.1000E 01	-0.4600E 03	0	0	0.0
205	0	0	-0.1000E 01	-0.4600E 03	0	0	0.0
206	0	0	-0.1000E 01	-0.4600E 03	0	0	0.0

CONSTANT TEMPERATURE NODE

END OF NODAL DATA

0 0 0 0 0

RESISTOR ID NUMBER

RESISTIVE DATA

1	1	2	0.8650E 00	0.0	0.0	0.0	0	0	0.0
2	1	11	0.3802E 03	0.0	0.0	0.0	0	0	0.0
3	2	12	0.3802E 03	0.0	0.0	0.0	0	0	0.0
4	3	4	0.9180E 00	0.0	0.0	0.0	0	0	0.0
5	5	6	0.9180E 00	0.0	0.0	0.0	0	0	0.0
6	7	8	0.9180E 00	0.0	0.0	0.0	0	0	0.0
7	9	10	0.9180E 00	0.0	0.0	0.0	0	0	0.0
8	3	11	0.6790E 01	0.0	0.0	0.0	0	0	0.0
9	4	12	0.6790E 01	0.0	0.0	0.0	0	0	0.0
10	5	11	0.6790E 01	0.0	0.0	0.0	0	0	0.0
11	6	12	0.6790E 01	0.0	0.0	0.0	0	0	0.0
12	7	11	0.6790E 01	0.0	0.0	0.0	0	0	0.0
13	8	12	0.6790E 01	0.0	0.0	0.0	0	0	0.0
14	9	11	0.6790E 01	0.0	0.0	0.0	0	0	0.0
15	10	12	0.6790E 01	0.0	0.0	0.0	0	0	0.0
16	3	5	0.4930E 01	0.0	0.0	0.0	0	0	0.0
17	4	6	0.4930E 01	0.0	0.0	0.0	0	0	0.0
18	5	7	0.4930E 01	0.0	0.0	0.0	0	0	0.0
19	6	8	0.4930E 01	0.0	0.0	0.0	0	0	0.0
20	7	9	0.4930E 01	0.0	0.0	0.0	0	0	0.0
21	8	10	0.4930E 01	0.0	0.0	0.0	0	0	0.0
22	3	9	0.4930E 01	0.0	0.0	0.0	0	0	0.0
23	4	10	0.4930E 01	0.0	0.0	0.0	0	0	0.0
24	25	28	0.1478E 04	0.0	0.0	0.0	0	0	0.0
25	26	29	0.1478E 04	0.0	0.0	0.0	0	0	0.0
26	27	30	0.1478E 04	0.0	0.0	0.0	0	0	0.0
27	28	31	0.1025E 04	0.0	0.0	0.0	0	0	0.0
28	29	31	0.1025E 04	0.0	0.0	0.0	0	0	0.0
29	30	31	0.1025E 04	0.0	0.0	0.0	0	0	0.0
30	28	30	0.1252E 05	0.0	0.0	0.0	0	0	0.0
31	28	29	0.1252E 05	0.0	0.0	0.0	0	0	0.0

INTERCONNECTING NODE j

CONDUCTION RESISTANCE (MIN°F/BTU)

INTERCONNECTING NODE i

RESISTIVE DATA

32	29	30	0.1252E 05	0.0	0.0	0.0	0	0	0.0
33	32	35	0.2286E 04	0.0	0.0	0.0	0	0	0.0
34	33	36	0.2286E 04	0.0	0.0	0.0	0	0	0.0
35	34	37	0.2286E 04	0.0	0.0	0.0	0	0	0.0
36	35	38	0.1104E 04	0.0	0.0	0.0	0	0	0.0
37	36	38	0.1104E 04	0.0	0.0	0.0	0	0	0.0
38	37	38	0.1104E 04	0.0	0.0	0.0	0	0	0.0
39	35	37	0.4402E 05	0.0	0.0	0.0	0	0	0.0
40	35	36	0.4402E 05	0.0	0.0	0.0	0	0	0.0
41	36	37	0.4402E 05	0.0	0.0	0.0	0	0	0.0
42	25	32	0.1595E 04	0.0	0.0	0.0	0	0	0.0
43	26	33	0.1595E 04	0.0	0.0	0.0	0	0	0.0
44	27	34	0.1595E 04	0.0	0.0	0.0	0	0	0.0
45	28	35	0.2711E 04	0.0	0.0	0.0	0	0	0.0
46	29	36	0.2711E 04	0.0	0.0	0.0	0	0	0.0
47	30	37	0.2711E 04	0.0	0.0	0.0	0	0	0.0
48	31	38	0.2711E 04	0.0	0.0	0.0	0	0	0.0
49	39	40	0.1740E 05	0.0	0.0	0.0	0	0	0.0
50	40	41	0.1740E 05	0.0	0.0	0.0	0	0	0.0
51	39	41	0.1740E 05	0.0	0.0	0.0	0	0	0.0
52	32	39	0.3216E 04	0.0	0.0	0.0	0	0	0.0
53	33	40	0.3216E 04	0.0	0.0	0.0	0	0	0.0
54	34	41	0.3216E 04	0.0	0.0	0.0	0	0	0.0
55	35	39	0.2573E 04	0.0	0.0	0.0	0	0	0.0
56	36	40	0.2573E 04	0.0	0.0	0.0	0	0	0.0
57	37	41	0.2573E 04	0.0	0.0	0.0	0	0	0.0
58	38	39	0.4288E 04	0.0	0.0	0.0	0	0	0.0
59	38	40	0.4288E 04	0.0	0.0	0.0	0	0	0.0
60	38	41	0.4288E 04	0.0	0.0	0.0	0	0	0.0
61	39	42	0.6497E 04	0.0	0.0	0.0	0	0	0.0
62	40	42	0.6497E 04	0.0	0.0	0.0	0	0	0.0
63	41	42	0.6497E 04	0.0	0.0	0.0	0	0	0.0
64	43	44	0.9570E 02	0.0	0.0	0.0	0	0	0.0
65	43	45	0.9570E 02	0.0	0.0	0.0	0	0	0.0
66	43	46	0.9570E 02	0.0	0.0	0.0	0	0	0.0
67	44	45	0.8214E 06	0.0	0.0	0.0	0	0	0.0
68	45	46	0.8214E 06	0.0	0.0	0.0	0	0	0.0
69	44	46	0.8214E 06	0.0	0.0	0.0	0	0	0.0
70	25	44	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
71	26	45	* 0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
72	27	46	$\boxed{0.1667E-01}$	0.6054E-13	0.2120E-02	0.0	0	0	0.0
73	44	47	0.1796E 05	0.0	0.0	0.0	0	0	0.0
74	45	48	0.1796E 05	0.0	0.0	0.0	0	0	0.0
75	46	49	0.1796E 05	0.0	0.0	0.0	0	0	0.0
76	44	11	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
77	45	11	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
78	46	11	0.1657E-01	$\boxed{0.4483E-14}$	0.1570E-03	0.0	0	0	0.0
79	47	48	0.4039E 06	0.0	0.0	0.0	0	0	0.0
80	49	49	0.4039E 06	0.0	0.0	0.0	0	0	0.0
81	47	49	0.4039E 06	0.0	0.0	0.0	0	0	0.0
82	47	25	0.1120E-02	0.3198E-13	$\boxed{0.1667E-01}$	0.0	0	0	0.0

$\frac{1}{60}\left[\frac{HR}{MIN}\right]$ $\frac{\sigma \mathcal{F} A}{60}\left[\frac{BTU}{MIN\ R^4}\right]$ $\mathcal{F}A\ (FT^2)$

* STEFAN-BOLTZMAN[illegible]

RESISTIVE DATA

(CONTINUED)

83	49	26	0.1120E-02	0.3198E-13	0.1667E-01	0.0	0	0	0.0
84	49	27	0.1120E-02	0.3198E-13	0.1667E-01	0.0	0	0	0.0
85	47	25	0.1000E 07	0.0	0.0	0.0	0	0	0.0
86	48	26	0.1000E 07	0.0	0.0	0.0	0	0	0.0
87	49	27	0.1000E 07	0.0	0.0	0.0	0	0	0.0
88	47	11	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
89	48	11	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
90	49	11	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
91	47	11	0.9520E 02	0.0	0.0	0.0	0	0	0.0
92	48	11	0.9520E 02	0.0	0.0	0.0	0	0	0.0
93	49	11	0.9520E 02	0.0	0.0	0.0	0	0	0.0
94	25	201	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
95	26	201	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
96	27	201	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
97	28	201	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
98	29	201	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
99	30	201	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
100	31	201	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
101	32	11	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
102	33	11	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
103	34	11	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
104	39	11	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
105	40	11	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
106	41	11	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
107	42	11	0.1667E-01	0.7225E-14	0.2530E-03	0.0	0	0	0.0
108	50	53	0.1478E 04	0.0	0.0	0.0	0	0	0.0
109	51	54	0.1478E 04	0.0	0.0	0.0	0	0	0.0
110	52	55	0.1478E 04	0.0	0.0	0.0	0	0	0.0
111	53	56	0.1025E 04	0.0	0.0	0.0	0	0	0.0
112	54	56	0.1025E 04	0.0	0.0	0.0	0	0	0.0
113	55	56	0.1025E 04	0.0	0.0	0.0	0	0	0.0
114	53	55	0.1252E 05	0.0	0.0	0.0	0	0	0.0
115	53	54	0.1252E 05	0.0	0.0	0.0	0	0	0.0
116	54	55	0.1252E 05	0.0	0.0	0.0	0	0	0.0
117	57	60	0.2286E 04	0.0	0.0	0.0	0	0	0.0
118	58	61	0.2286E 04	0.0	0.0	0.0	0	0	0.0
119	59	62	0.2286E 04	0.0	0.0	0.0	0	0	0.0
120	60	63	0.1104E 04	0.0	0.0	0.0	0	0	0.0
121	61	63	0.1104E 04	0.0	0.0	0.0	0	0	0.0
122	62	63	0.1104E 04	0.0	0.0	0.0	0	0	0.0
123	60	62	0.4402E 05	0.0	0.0	0.0	0	0	0.0
124	60	61	0.4402E 05	0.0	0.0	0.0	0	0	0.0
125	61	62	0.4402E 05	0.0	0.0	0.0	0	0	0.0
126	50	57	0.1595E 04	0.0	0.0	0.0	0	0	0.0
127	51	58	0.1595E 04	0.0	0.0	0.0	0	0	0.0
128	52	59	0.1595E 04	0.0	0.0	0.0	0	0	0.0
129	53	60	0.2711E 04	0.0	0.0	0.0	0	0	0.0
130	54	61	0.2711E 04	0.0	0.0	0.0	0	0	0.0
131	55	62	0.2711E 04	0.0	0.0	0.0	0	0	0.0
132	56	63	0.2711E 04	0.0	0.0	0.0	0	0	0.0
133	64	65	0.1740E 05	0.0	0.0	0.0	0	0	0.0

RESISTIVE DATA

(CONTINUED)

134	65	66	0.1740E 05	0.0	0.0	0.0	0	0	0.0
135	64	66	0.1740E 05	0.0	0.0	0.0	0	0	0.0
136	57	64	0.3216E 04	0.0	0.0	0.0	0	0	0.0
137	58	65	0.3216E 04	0.0	0.0	0.0	0	0	0.0
138	59	66	0.3216E 04	0.0	0.0	0.0	0	0	0.0
139	60	64	0.2573E 04	0.0	0.0	0.0	0	0	0.0
140	61	65	0.2573E 04	0.0	0.0	0.0	0	0	0.0
141	62	66	0.2573E 04	0.0	0.0	0.0	0	0	0.0
142	63	64	0.4288E 04	0.0	0.0	0.0	0	0	0.0
143	63	65	0.4288E 04	0.0	0.0	0.0	0	0	0.0
144	63	66	0.4288E 04	0.0	0.0	0.0	0	0	0.0
145	64	67	0.6497E 04	0.0	0.0	0.0	0	0	0.0
146	65	67	0.6497E 04	0.0	0.0	0.0	0	0	0.0
147	66	67	0.6497E 04	0.0	0.0	0.0	0	0	0.0
148	68	69	0.9570E 02	0.0	0.0	0.0	0	0	0.0
149	68	70	0.9570E 02	0.0	0.0	0.0	0	0	0.0
150	68	71	0.9570E 02	0.0	0.0	0.0	0	0	0.0
151	69	70	0.8214E 06	0.0	0.0	0.0	0	0	0.0
152	70	71	0.8214E 06	0.0	0.0	0.0	0	0	0.0
153	69	71	0.9214E 06	0.0	0.0	0.0	0	0	0.0
154	69	50	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
155	70	51	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
156	71	52	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
157	69	72	0.1796E 05	0.0	0.0	0.0	0	0	0.0
158	70	73	0.1796E 05	0.0	0.0	0.0	0	0	0.0
159	71	74	0.1796E 05	0.0	0.0	0.0	0	0	0.0
160	69	3	0.1570E-03	0.4483E-14	0.1667E-01	0.0	0	0	0.0
161	70	3	0.1570E-03	0.4483E-14	0.1667E-01	0.0	0	0	0.0
162	71	3	0.1570E-03	0.4483E-14	0.1667E-01	0.0	0	0	0.0
163	72	73	0.4039E 06	0.0	0.0	0.0	0	0	0.0
164	73	74	0.4039E 06	0.0	0.0	0.0	0	0	0.0
165	72	74	0.4039E 06	0.0	0.0	0.0	0	0	0.0
166	72	50	0.1667E-01	0.3198E-13	0.1120E-02	0.0	0	0	0.0
167	73	51	0.1667E-01	0.3198E-13	0.1120E-02	0.0	0	0	0.0
168	74	52	0.1667E-01	0.3198E-13	0.1120E-02	0.0	0	0	0.0
169	72	50	0.1000E 07	0.0	0.0	0.0	0	0	0.0
170	73	51	0.1000E 07	0.0	0.0	0.0	0	0	0.0
171	74	52	0.1000E 07	0.0	0.0	0.0	0	0	0.0
172	72	3	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
173	73	3	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
174	74	3	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
175	72	3	0.9520E 02	0.0	0.0	0.0	0	0	0.0
176	73	3	0.9520E 02	0.0	0.0	0.0	0	0	0.0
177	74	3	0.9520E 02	0.0	0.0	0.0	0	0	0.0
178	50	202	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
179	51	202	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
180	52	202	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
181	53	202	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
182	54	202	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
183	55	202	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
184	56	202	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0

RESISTIVE DATA

(CONTINUED)

185	57	3	0.1657E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
196	58	3	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
187	59	3	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
198	64	3	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
199	65	3	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
190	66	3	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
200	67	3	0.1667E-01	0.7225E-14	0.2530E-03	0.0	0	0	0.0
201	75	78	0.1478E 04	0.0	0.0	0.0	0	0	0.0
202	76	79	0.1478E 04	0.0	0.0	0.0	0	0	0.0
203	77	80	0.1478E 04	0.0	0.0	0.0	0	0	0.0
204	78	81	0.1025E 04	0.0	0.0	0.0	0	0	0.0
205	79	81	0.1025E 04	0.0	0.0	0.0	0	0	0.0
206	80	81	0.1025E 04	0.0	0.0	0.0	0	0	0.0
207	78	80	0.1252E 05	0.0	0.0	0.0	0	0	0.0
208	78	79	0.1252E 05	0.0	0.0	0.0	0	0	0.0
209	79	80	0.1252E 05	0.0	0.0	0.0	0	0	0.0
210	82	85	0.2286E 04	0.0	0.0	0.0	0	0	0.0
211	83	86	0.2286E 04	0.0	0.0	0.0	0	0	0.0
212	84	87	0.2286E 04	0.0	0.0	0.0	0	0	0.0
213	85	88	0.1104E 04	0.0	0.0	0.0	0	0	0.0
214	86	88	0.1104E 04	0.0	0.0	0.0	0	0	0.0
215	87	88	0.1104E 04	0.0	0.0	0.0	0	0	0.0
216	85	87	0.4402E 05	0.0	0.0	0.0	0	0	0.0
217	85	86	0.4402E 05	0.0	0.0	0.0	0	0	0.0
218	86	87	0.4402E 05	0.0	0.0	0.0	0	0	0.0
219	75	82	0.1595E 04	0.0	0.0	0.0	0	0	0.0
220	76	83	0.1595E 04	0.0	0.0	0.0	0	0	0.0
221	77	84	0.1595E 04	0.0	0.0	0.0	0	0	0.0
222	78	85	0.2711E 04	0.0	0.0	0.0	0	0	0.0
223	79	86	0.2711E 04	0.0	0.0	0.0	0	0	0.0
224	80	87	0.2711E 04	0.0	0.0	0.0	0	0	0.0
225	81	88	0.2711E 04	0.0	0.0	0.0	0	0	0.0
226	89	90	0.1740E 05	0.0	0.0	0.0	0	0	0.0
227	90	91	0.1740E 05	0.0	0.0	0.0	0	0	0.0
228	89	91	0.1740E 05	0.0	0.0	0.0	0	0	0.0
229	82	89	0.3216E 04	0.0	0.0	0.0	0	0	0.0
230	83	90	0.3216E 04	0.0	0.0	0.0	0	0	0.0
231	84	91	0.3216E 04	0.0	0.0	0.0	0	0	0.0
232	85	89	0.2573E 04	0.0	0.0	0.0	0	0	0.0
233	86	90	0.2573E 04	0.0	0.0	0.0	0	0	0.0
234	87	91	0.2573E 04	0.0	0.0	0.0	0	0	0.0
235	88	89	0.4288E 04	0.0	0.0	0.0	0	0	0.0
236	88	90	0.4288E 04	0.0	0.0	0.0	0	0	0.0
237	88	91	0.4288E 04	0.0	0.0	0.0	0	0	0.0
238	89	92	0.6497E 04	0.0	0.0	0.0	0	0	0.0
239	90	92	0.6497E 04	0.0	0.0	0.0	0	0	0.0
240	91	92	0.6497E 04	0.0	0.0	0.0	0	0	0.0
241	93	94	0.9570E 02	0.0	0.0	0.0	0	0	0.0
242	93	95	0.9570E 02	0.0	0.0	0.0	0	0	0.0
243	93	96	0.9570E 02	0.0	0.0	0.0	0	0	0.0
244	94	95	0.8214E 06	0.0	0.0	0.0	0	0	0.0

RESISTIVE DATA

(CONTINUED)

245	95	96	0.8214E 06	0.0	0.0	0.0	0	0	0.0
246	94	96	0.8214E 06	0.0	0.0	0.0	0	0	0.0
247	94	75	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
248	95	76	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
249	96	77	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
250	94	97	0.1796E 05	0.0	0.0	0.0	0	0	0.0
251	95	98	0.1796E 05	0.0	0.0	0.0	0	0	0.0
252	96	99	0.1796E 05	0.0	0.0	0.0	0	0	0.0
253	94	12	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
254	95	12	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
255	96	12	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
256	97	98	0.4039E 06	0.0	0.0	0.0	0	0	0.0
257	98	99	0.4039E 06	0.0	0.0	0.0	0	0	0.0
258	97	99	0.4039E 06	0.0	0.0	0.0	0	0	0.0
259	97	75	0.1120E-02	0.3198E-13	0.1667E-01	0.0	0	0	0.0
260	98	76	0.1120E-02	0.3198E-13	0.1667E-01	0.0	0	0	0.0
261	99	77	0.1120E-02	0.3198E-13	0.1667E-01	0.0	0	0	0.0
262	97	75	0.1000E 07	0.0	0.0	0.0	0	0	0.0
263	98	76	0.1000E 07	0.0	0.0	0.0	0	0	0.0
264	99	77	0.1000E 07	0.0	0.0	0.0	0	0	0.0
265	97	12	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
266	98	12	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
267	99	12	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
268	97	12	0.9520E 02	0.0	0.0	0.0	0	0	0.0
269	98	12	0.9520E 02	0.0	0.0	0.0	0	0	0.0
270	99	12	0.9520E 02	0.0	0.0	0.0	0	0	0.0
271	75	203	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
272	76	203	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
273	77	203	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
274	78	203	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
275	79	203	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
276	80	203	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
277	81	203	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
278	82	12	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
279	83	12	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
280	84	12	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
281	89	12	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
282	90	12	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
283	91	12	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
284	92	12	0.1667E-01	0.7225E-14	0.2530E-03	0.0	0	0	0.0
285	100	103	0.1478E 04	0.0	0.0	0.0	0	0	0.0
286	101	104	0.1478E 04	0.0	0.0	0.0	0	0	0.0
287	102	105	0.1478E 04	0.0	0.0	0.0	0	0	0.0
288	103	106	0.1025E 04	0.0	0.0	0.0	0	0	0.0
289	104	106	0.1025E 04	0.0	0.0	0.0	0	0	0.0
290	105	106	0.1025E 04	0.0	0.0	0.0	0	0	0.0
291	103	105	0.1252E 05	0.0	0.0	0.0	0	0	0.0
292	103	104	0.1252E 05	0.0	0.0	0.0	0	0	0.0
293	104	105	0.1252E 05	0.0	0.0	0.0	0	0	0.0
294	107	110	0.2286E 04	0.0	0.0	0.0	0	0	0.0
295	108	111	0.2286E 04	0.0	0.0	0.0	0	0	0.0

RESISTIVE DATA
(CONTINUED)

296	109	112	0.2286E 04	0.0	0.0	0.0	0	0	0.0
297	110	113	0.1104E 04	0.0	0.0	0.0	0	0	0.0
298	111	113	0.1104E 04	0.0	0.0	0.0	0	0	0.0
299	112	113	0.1104E 04	0.0	0.0	0.0	0	0	0.0
300	110	112	0.4402E 05	0.0	0.0	0.0	0	0	0.0
301	110	111	0.4402E 05	0.0	0.0	0.0	0	0	0.0
302	111	112	0.4402E 05	0.0	0.0	0.0	0	0	0.0
303	100	107	0.1595E 04	0.0	0.0	0.0	0	0	0.0
304	101	108	0.1595E 04	0.0	0.0	0.0	0	0	0.0
305	102	109	0.1595E 04	0.0	0.0	0.0	0	0	0.0
306	103	110	0.2711E 04	0.0	0.0	0.0	0	0	0.0
307	104	111	0.2711E 04	0.0	0.0	0.0	0	0	0.0
308	105	112	0.2711E 04	0.0	0.0	0.0	0	0	0.0
309	106	113	0.2711E 04	0.0	0.0	0.0	0	0	0.0
310	114	115	0.1740E 05	0.0	0.0	0.0	0	0	0.0
311	115	116	0.1740E 05	0.0	0.0	0.0	0	0	0.0
312	114	116	0.1740E 05	0.0	0.0	0.0	0	0	0.0
313	107	114	0.3216E 04	0.0	0.0	0.0	0	0	0.0
314	108	115	0.3216E 04	0.0	0.0	0.0	0	0	0.0
315	109	116	0.3216E 04	0.0	0.0	0.0	0	0	0.0
316	110	114	0.2573E 04	0.0	0.0	0.0	0	0	0.0
317	111	115	0.2573E 04	0.0	0.0	0.0	0	0	0.0
318	112	116	0.2573E 04	0.0	0.0	0.0	0	0	0.0
319	113	114	0.4288E 04	0.0	0.0	0.0	0	0	0.0
320	113	115	0.4288E 04	0.0	0.0	0.0	0	0	0.0
321	113	116	0.4288E 04	0.0	0.0	0.0	0	0	0.0
322	114	117	0.6497E 04	0.0	0.0	0.0	0	0	0.0
323	115	117	0.6497E 04	0.0	0.0	0.0	0	0	0.0
324	116	117	0.6497E 04	0.0	0.0	0.0	0	0	0.0
325	118	119	0.9570E 02	0.0	0.0	0.0	0	0	0.0
326	118	120	0.9570E 02	0.0	0.0	0.0	0	0	0.0
327	118	121	0.9570E 02	0.0	0.0	0.0	0	0	0.0
328	119	120	0.8214E 06	0.0	0.0	0.0	0	0	0.0
329	120	121	0.8214E 06	0.0	0.0	0.0	0	0	0.0
330	119	121	0.8214E 06	0.0	0.0	0.0	0	0	0.0
331	119	100	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
332	120	101	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
333	121	102	0.1667E-01	0.6054E-13	0.2120E-02	0.0	0	0	0.0
334	119	122	0.1796E 05	0.0	0.0	0.0	0	0	0.0
335	120	123	0.1796E 05	0.0	0.0	0.0	0	0	0.0
336	121	124	0.1796E 05	0.0	0.0	0.0	0	0	0.0
337	119	5	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
338	120	5	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
339	121	5	0.1667E-01	0.4483E-14	0.1570E-03	0.0	0	0	0.0
340	122	123	0.4039E 06	0.0	0.0	0.0	0	0	0.0
341	123	124	0.4039E 06	0.0	0.0	0.0	0	0	0.0
342	122	124	0.4039E 06	0.0	0.0	0.0	0	0	0.0
343	122	100	0.1667E-01	0.3198E-13	0.1120E-02	0.0	0	0	0.0
344	123	101	0.1667E-01	0.3198E-13	0.1120E-02	0.0	0	0	0.0
345	124	102	0.1667E-01	0.3198E-13	0.1120E-02	0.0	0	0	0.0
346	122	100	0.1000E 07	0.0	0.0	0.0	0	0	0.0

RESISTIVE DATA

(CONTINUED)

347	123	101	0.1000E 07	0.0	0.0	0.0	0	0	0.0
348	124	102	0.1000E 07	0.0	0.0	0.0	0	0	0.0
349	122	5	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
350	123	5	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
351	124	5	0.1667E-01	0.2384E-14	0.8350E-04	0.0	0	0	0.0
352	122	5	0.9520E 02	0.0	0.0	0.0	0	0	0.0
353	123	5	0.9520E 02	0.0	0.0	0.0	0	0	0.0
354	124	5	0.9520E 02	0.0	0.0	0.0	0	0	0.0
355	100	206	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
356	101	206	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
357	102	206	0.1667E-01	0.6139E-13	0.2150E-02	0.0	0	0	0.0
358	103	206	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
359	104	206	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
360	105	206	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
361	106	206	0.1667E-01	0.3255E-13	0.1140E-02	0.0	0	0	0.0
362	107	5	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
363	108	5	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
364	109	5	0.1667E-01	0.8024E-14	0.2810E-03	0.0	0	0	0.0
365	114	5	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
366	115	5	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
367	116	5	0.1667E-01	0.7167E-14	0.2510E-03	0.0	0	0	0.0
368	117	5	0.1667E-01	0.7225E-14	0.2530E-03	0.0	0	0	0.0
369	135	145	0.4560E 00	0.0	0.0	0.0	0	0	0.0
370	136	146	0.9250E 00	0.0	0.0	0.0	0	0	0.0
371	137	147	0.8990E 00	0.0	0.0	0.0	0	0	0.0
372	138	148	0.4560E 00	0.0	0.0	0.0	0	0	0.0
373	139	149	0.8990E 00	0.0	0.0	0.0	0	0	0.0
374	140	150	0.8990E 00	0.0	0.0	0.0	0	0	0.0
375	141	151	0.8990E 00	0.0	0.0	0.0	0	0	0.0
376	142	152	0.8990E 00	0.0	0.0	0.0	0	0	0.0
377	143	153	0.9250E 00	0.0	0.0	0.0	0	0	0.0
378	144	154	0.8990E 00	0.0	0.0	0.0	0	0	0.0
385	11	145	0.1667E-01	0.9423E-12	0.3300E-01	0.0	0	0	0.0
386	3	146	0.1667E-01	0.4626E-12	0.1620E-01	0.0	0	0	0.0
387	4	147	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
388	12	148	0.1667E-01	0.9423E-12	0.3300E-01	0.0	0	0	0.0
389	7	149	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
390	8	150	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
391	9	151	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
392	10	152	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
393	5	153	0.1667E-01	0.4626E-12	0.1620E-01	0.0	0	0	0.0
394	6	154	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
395	125	155	0.1667E-01	0.6711E-11	0.2350E 00	0.0	0	0	0.0
396	126	156	0.1667E-01	0.3312E-11	0.1160E 00	0.0	0	0	0.0
397	127	157	0.1667E-01	0.3398E-11	0.1190E 00	0.0	0	0	0.0
398	128	158	0.1667E-01	0.6711E-11	0.2350E 00	0.0	0	0	0.0
399	129	159	0.1667E-01	0.3398E-11	0.1190E 00	0.0	0	0	0.0
400	130	160	0.1667E-01	0.3398E-11	0.1190E 00	0.0	0	0	0.0
401	131	161	0.1667E-01	0.3398E-11	0.1190E 00	0.0	0	0	0.0
402	132	162	0.1667E-01	0.3398E-11	0.1190E 00	0.0	0	0	0.0
403	133	163	0.1667E-01	0.3312E-11	0.1160E 00	0.0	0	0	0.0

RESISTIVE DATA

(CONTINUED)

404	134	164	0.1667E-01	0.3398E-11	0.1190E 00	0.0	0	0	0.0
405	125	155	0.4762E 04	0.0	0.0	0.0	0	0	0.0
406	126	156	0.9662E 04	0.0	0.0	0.0	0	0	0.0
407	127	157	0.9390E 04	0.0	0.0	0.0	0	0	0.0
408	128	158	0.4762E 04	0.0	0.0	0.0	0	0	0.0
409	129	159	0.9390E 04	0.0	0.0	0.0	0	0	0.0
410	130	160	0.9390E 04	0.0	0.0	0.0	0	0	0.0
411	131	161	0.9390E 04	0.0	0.0	0.0	0	0	0.0
412	132	162	0.9390E 04	0.0	0.0	0.0	0	0	0.0
413	133	163	0.9662E 04	0.0	0.0	0.0	0	0	0.0
414	134	164	0.9390E 04	0.0	0.0	0.0	0	0	0.0
415	11	155	0.1667E-01	0.5026E-12	0.1760E-01	0.0	0	0	0.0
416	3	156	0.1667E-01	0.2473E-12	0.8660E-02	0.0	0	0	0.0
417	4	157	0.1667E-01	0.2544E-12	0.8910E-02	0.0	0	0	0.0
418	12	158	0.1667E-01	0.5026E-12	0.1760E-01	0.0	0	0	0.0
419	7	159	0.1667E-01	0.2544E-12	0.8910E-02	0.0	0	0	0.0
420	8	160	0.1667E-01	0.2544E-12	0.8910E-02	0.0	0	0	0.0
421	9	161	0.1667E-01	0.2544E-12	0.8910E-02	0.0	0	0	0.0
422	10	162	0.1667E-01	0.2544E-12	0.8910E-02	0.0	0	0	0.0
423	5	163	0.1667E-01	0.2473E-12	0.8660E-02	0.0	0	0	0.0
424	6	164	0.1667E-01	0.2544E-12	0.8910E-02	0.0	0	0	0.0
425	11	155	0.4530E 00	0.0	0.0	0.0	0	0	0.0
426	3	156	0.9190E 00	0.0	0.0	0.0	0	0	0.0
427	4	157	0.8930E 00	0.0	0.0	0.0	0	0	0.0
428	12	158	0.4530E 00	0.0	0.0	0.0	0	0	0.0
429	7	159	0.8930E 00	0.0	0.0	0.0	0	0	0.0
430	8	160	0.8930E 00	0.0	0.0	0.0	0	0	0.0
431	9	161	0.8930E 00	0.0	0.0	0.0	0	0	0.0
432	10	162	0.8930E 00	0.0	0.0	0.0	0	0	0.0
433	5	163	0.9190E 00	0.0	0.0	0.0	0	0	0.0
434	6	164	0.8930E 00	0.0	0.0	0.0	0	0	0.0
435	125	201	0.1667E-01	0.2199E-10	0.7700E 00	0.0	0	0	0.0
436	126	202	0.1667E-01	0.1085E-10	0.3800E 00	0.0	0	0	0.0
437	127	202	0.1667E-01	0.1117E-10	0.3910E 00	0.0	0	0	0.0
438	128	203	0.1667E-01	0.2199E-10	0.7700E 00	0.0	0	0	0.0
439	129	204	0.1667E-01	0.1117E-10	0.3910E 00	0.0	0	0	0.0
440	130	204	0.1667E-01	0.1117E-10	0.3910E 00	0.0	0	0	0.0
441	131	205	0.1667E-01	0.1117E-10	0.3910E 00	0.0	0	0	0.0
442	132	205	0.1667E-01	0.1117E-10	0.3910E 00	0.0	0	0	0.0
443	133	206	0.1667E-01	0.1085E-10	0.3800E 00	0.0	0	0	0.0
444	134	206	0.1667E-01	0.1117E-10	0.3910E 00	0.0	0	0	0.0
445	125	11	0.1667E-01	0.3712E-11	0.1300E 00	0.0	0	0	0.0
446	126	3	0.1667E-01	0.1822E-11	0.6380E-01	0.0	0	0	0.0
447	127	4	0.1667E-01	0.1876E-11	0.6570E-01	0.0	0	0	0.0
448	128	12	0.1667E-01	0.3712E-11	0.1300E 00	0.0	0	0	0.0
449	129	7	0.1667E-01	0.1876E-11	0.6570E-01	0.0	0	0	0.0
450	130	8	0.1667E-01	0.1876E-11	0.6570E-01	0.0	0	0	0.0
451	131	9	0.1667E-01	0.1876E-11	0.6570E-01	0.0	0	0	0.0
452	132	10	0.1667E-01	0.1876E-11	0.6570E-01	0.0	0	0	0.0
453	133	5	0.1667E-01	0.1822E-11	0.6380E-01	0.0	0	0	0.0
454	134	6	0.1667E-01	0.1876E-11	0.6570E-01	0.0	0	0	0.0

RESISTIVE DATA
(CONTINUED)

455	135	201	0.1667E-01	0.6425E-12	0.2250E-01	0.0	0	0	0.0
456	136	202	0.1667E-01	0.3170E-12	0.1110E-01	0.0	0	0	0.0
457	137	202	0.1667E-01	0.3255E-12	0.1140E-01	0.0	0	0	0.0
458	138	203	0.1667E-01	0.6425E-12	0.2250E-01	0.0	0	0	0.0
459	139	204	0.1667E-01	0.3255E-12	0.1140E-01	0.0	0	0	0.0
460	140	204	0.1667E-01	0.3255E-12	0.1140E-01	0.0	0	0	0.0
461	141	205	0.1667E-01	0.3255E-12	0.1140E-01	0.0	0	0	0.0
462	142	205	0.1667E-01	0.3255E-12	0.1140E-01	0.0	0	0	0.0
463	143	206	0.1667E-01	0.3170E-12	0.1110E-01	0.0	0	0	0.0
464	144	206	0.1667E-01	0.3255E-12	0.1140E-01	0.0	0	0	0.0
465	43	201	0.1667E-01	0.9195E-14	0.3220E-03	0.0	0	0	0.0
466	68	202	0.1667E-01	0.9195E-14	0.3220E-03	0.0	0	0	0.0
467	93	203	0.1667E-01	0.9195E-14	0.3220E-03	0.0	0	0	0.0
468	118	206	0.1667E-01	0.9195E-14	0.3220E-03	0.0	0	0	0.0
469	11	201	0.1667E-01	0.9538E-12	0.3340E-01	0.0	0	0	0.0
470	3	202	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
471	4	202	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
472	12	203	0.1667E-01	0.9538E-12	0.3340E-01	0.0	0	0	0.0
473	7	204	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
474	8	204	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
475	9	205	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
476	10	205	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
477	5	206	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
478	6	206	0.1667E-01	0.4769E-12	0.1670E-01	0.0	0	0	0.0
479	125	145	0.1667E-01	0.1271E-10	0.4450E 00	0.0	0	0	0.0
480	126	146	0.1667E-01	0.6254E-11	0.2190E 00	0.0	0	0	0.0
481	127	147	0.1667E-01	0.6454E-11	0.2260E 00	0.0	0	0	0.0
482	128	148	0.1667E-01	0.1271E-10	0.4450E 00	0.0	0	0	0.0
483	129	149	0.1667E-01	0.6454E-11	0.2260E 00	0.0	0	0	0.0
484	130	150	0.1667E-01	0.6454E-11	0.2260E 00	0.0	0	0	0.0
485	131	151	0.1667E-01	0.6454E-11	0.2260E 00	0.0	0	0	0.0
486	132	152	0.1667E-01	0.6454E-11	0.2260E 00	0.0	0	0	0.0
487	133	153	0.1667E-01	0.6254E-11	0.2190E 00	0.0	0	0	0.0
488	134	154	0.1667E-01	0.6454E-11	0.2260E 00	0.0	0	0	0.0
489	145	155	0.8550E 02	0.0	0.0	0.0	0	0	0.0
490	146	156	0.1736E 03	0.0	0.0	0.0	0	0	0.0
491	147	157	0.1687E 03	0.0	0.0	0.0	0	0	0.0
492	148	158	0.8550E 02	0.0	0.0	0.0	0	0	0.0
493	149	159	0.1687E 03	0.0	0.0	0.0	0	0	0.0
494	150	160	0.1687E 03	0.0	0.0	0.0	0	0	0.0
495	151	161	0.1687E 03	0.0	0.0	0.0	0	0	0.0
496	152	162	0.1687E 03	0.0	0.0	0.0	0	0	0.0
497	153	163	0.1736E 03	0.0	0.0	0.0	0	0	0.0
498	154	164	0.1687E 03	0.0	0.0	0.0	0	0	0.0

0 0 0 0 0

END OF RESISTIVE DATA

9 PROBLEM CONSTANTS FUNCTION NUMBER

0	1	0.0					
		0.0	0.1000E 02	0.0	0.2255E 03	0.0	0.0
-1	0	0	0.0				
-1	0	0	0.0				

PRINT OUT INTERVAL (MINUTES)

ORBITAL PERIOD (MINUTES)

PROBLEM CONSTANT DATA

TABLE NUMBER

INDEPENDENT VARIABLE, TIME

```
    0    0         76    0    0    0    0
```

HEATING RATE (BTU/MIN)

```
    1    0    4    0.2255E 03 0.0
                   0.0        0.7320E 01 0.2255E 03 0.7320E 01
   -1    0    0    0.0
```

ORBITAL PERIOD (MINUTES)

```
    2    0    4    0.2255E 03 0.0
                   0.0        0.1870E-01 0.1880E 02 0.6080E-01 0.3760E 02 0.5260E-01 0.5640E 02 0.1370E-01
                   0.7520E 02 0.0        0.1503E 03 0.0        0.1691E 03 0.9220E-03 0.1879E 03 0.3910E-02
                   0.2067E 03 0.6750E-02 0.2255E 03 0.1870E-01
   -1    0    0    0.0
```

HEATING RATE (BTU/MIN)

TIME — HEATING RATE (DATA PAIRS) — (DATA PAIRS)

TIME (MINUTES)

```
    3    0    4    0.2255E 03 0.0
                   0.0        0.4480E-02 0.1880E 02 0.3100E-01 0.3760E 02 0.6580E-01 0.5640E 02 0.8000E-01
                   0.7520E 02 0.5900E-01 0.9400E 02 0.2250E-01 0.1128E 03 0.1860E-02 0.1315E 03 0.7850E-03
                   0.1503E 03 0.2870E-03 0.1691E 03 0.1700E-03 0.1879E 03 0.2880E-03 0.2067E 03 0.7850E-03
                   0.2255E 03 0.4880E-02
   -1    0    0    0.0

    4    0    4    0.2255E 03 0.0
                   0.0        0.0        0.3760E 02 0.0        0.5640E 02 0.1370E-01 0.7520E 02 0.4710E-01
                   0.9400E 02 0.4460E-01 0.1128E 03 0.7780E-02 0.1315E 03 0.6750E-02 0.1503E 03 0.3910E-02
                   0.1691E 03 0.9410E-03 0.1879E 03 0.0        0.2255E 03 0.0
   -1    0    0    0.0

    5    0    4    0.2255E 03 0.0
                   0.0        0.2260E-02 0.1880E 02 0.3310E-01 0.3760E 02 0.8550E-01 0.5640E 02 0.1070E 00
                   0.7520E 02 0.7660E-01 0.9400E 02 0.2420E-01 0.1128E 03 0.9410E-03 0.1315E 03 0.0
                   0.2067E 03 0.0        0.2255E 03 0.2260E-02
   -1    0    0    0.0

    6    0    4    0.2255E 03 0.0
                   0.0        0.2260E-02 0.1880E 02 0.0        0.9400E 02 0.0        0.1128E 03 0.9410E-03
                   0.1315E 03 0.3670E-02 0.1503E 03 0.6350E-02 0.1691E 03 0.7340E-02 0.1879E 03 0.6340E-02
                   0.2067E 03 0.3670E-02 0.2255E 03 0.2260E-02
   -1    0    0    0.0

    7    0    4    0.2255E 03 0.0
                   0.0        0.1690E-02 0.1880E 02 0.1420E-02 0.3760E 02 0.1290E-02 0.5640E 02 0.1260E-02
                   0.7520E 02 0.1290E-02 0.9400E 02 0.1420E-02 0.1128E 03 0.1690E-02 0.1315E 03 0.2080E-02
                   0.1503E 03 0.2440E-02 0.1691E 03 0.2590E-02 0.1879E 03 0.2440E-02 0.2067E 03 0.2080E-02
                   0.2255E 03 0.1690E-02
   -1    0    0    0.0
```

HEATING DATA

```
  8    0    4    0.2255E 03 0.0
                 0.0        0.3020E-02 0.1880E 02 0.2630E-02 0.3760E 02 0.1870E-02 0.5640E 02 0.1120E-02
                 0.7520E 02 0.8990E-03 0.9400E 02 0.9610E-03 0.1128E 03 0.1100E-02 0.1315E 03 0.1290E-02
                 0.1503E 03 0.1470E-02 0.1691E 03 0.1780E-02 0.1879E 03 0.2440E-02 0.2067E 03 0.2970E-02
                 0.2255E 03 0.3020E-02
 -1    0    0    0.0

  9    0    4    0.2255E 03 0.0
                 0.0        0.4670E-03 0.1880E 02 0.8560E-03 0.3760E 02 0.1220E-02 0.5640E 02 0.1370E-02
                 0.7520E 02 0.1220E-02 0.9400E 02 0.8560E-03 0.1128E 03 0.4670E-03 0.1315E 03 0.1960E-03
                 0.1503E 03 0.7170E-04 0.1691E 03 0.4230E-04 0.1879E 03 0.7170E-04 0.2067E 03 0.1960E-03
                 0.2255E 03 0.4670E-03
 -1    0    0    0.0

 10    0    4    0.2255E 03 0.0
                 0.0        0.4670E-03 0.1880E 02 0.0        0.9400E 02 0.0        0.1128E 03 0.4670E-03
                 0.1315E 03 0.1820E-02 0.1503E 03 0.3150E-02 0.1691E 03 0.3640E-02 0.1879E 03 0.3150E-02
                 0.2067E 03 0.1820E-02 0.2255E 03 0.4670E-03
 -1    0    0    0.0

 11    0    4    0.2255E 03 0.0
                 0.0        0.2330E-02 0.2255E 03 0.2330E-02
 -1    0    0    0.0

 12    0    4    0.2255E 03 0.0
                 0.0        0.1960E 00 0.1880E 02 0.1770E 00 0.3760E 02 0.1680E 00 0.5640E 02 0.1660E 00
                 0.7520E 02 0.1680E 00 0.9400E 02 0.1770E 00 0.1128E 03 0.1960E 00 0.1315E 03 0.2230E 00
                 0.1503E 03 0.2480E 00 0.1691E 03 0.2590E 00 0.1879E 03 0.2480E 00 0.2067E 03 0.2230E 00
                 0.2255E 03 0.1960E 00
 -1    0    0    0.0

 13    0    4    0.2255E 03 0.0
                 0.0        0.1370E 00 0.1880E 02 0.1190E 00 0.3760E 02 0.6900E-01 0.5640E 02 0.1660E-01
                 0.7520E 02 0.0        0.1503E 03 0.0        0.1691E 03 0.1660E-01 0.1879E 03 0.6900E-01
                 0.2067E 03 0.1190E 00 0.2255E 03 0.1370E 00
 -1    0    0    0.0

 14    0    4    0.2255E 03 0.0
                 0.0        0.3270E-01 0.1880E 02 0.6010E-01 0.3760E 02 0.8530E-01 0.5640E 02 0.9570E-01
                 0.7520E 02 0.8530E-01 0.9400E 02 0.6010E-01 0.1128E 03 0.3270E-01 0.1315E 03 0.1370E-01
                 0.1503E 03 0.5030E-02 0.1691E 03 0.2960E-02 0.1879E 03 0.5030E-02 0.2067E 03 0.1370E-01
                 0.2255E 03 0.3270E-01
 -1    0    0    0.0
```

HEATING DATA
(CONTINUED)

15	0	4	0.2255E 03	0.0						
			0.0	0.0	0.3760E 02	0.0	0.5640E 02	0.1660E-01	0.7520E 02	0.6900E-01
			0.9400E 02	0.1190E 00	0.1128E 03	0.1370E 00	0.1315E 03	0.1190E 00	0.1503E 03	0.6900E-01
			0.1691E 03	0.1660E-01	0.1879E 03	0.0	0.2255E 03	0.0		
-1	0	0	0.0							
16	0	4	0.2255E 03	0.0						
			0.0	0.1660E-01	0.1880E 02	0.6470E-01	0.3760E 02	0.1120E 00	0.5640E 02	0.1300E 00
			0.7520E 02	0.1120E 00	0.9400E 02	0.6470E-01	0.1128E 03	0.1660E-01	0.1315E 03	0.0
			0.7067E 03	0.0	0.2255E 03	0.1660E-01				
-1	0	0	0.0							
17	0	4	0.2255E 03	0.0						
			0.0	0.1660E-01	0.1880E 02	0.0	0.9400E 02	0.0	0.1128E 03	0.1660E-01
			0.1315E 03	0.6470E-01	0.1503E 03	0.1120E 00	0.1691E 03	0.1300E 00	0.1879E 03	0.1120E 00
			0.2067E 03	0.6470E-01	0.2255E 03	0.1660E-01				
-1	0	0	0.0							

HEATING DATA (CONTINUED)

18	0	4	0.2255E 03	0.0						
			0.0	0.1630E-04	0.1880E 02	0.5240E-04	0.3760E 02	0.9580E-04	0.5640E 02	0.1140E-03
			0.7520E 02	0.8900E-04	0.9400E 02	0.4410E-04	0.1128E 03	0.1360E-04	0.1315E 03	0.5750E-05
			0.1503E 03	0.2100E-05	0.1691E 03	0.1240E-05	0.1879E 03	0.2110E-05	0.2067E 03	0.5750E-05
			0.2255E 03	0.1630E-04						
-1	0	0	0.0							
19	0	4	0.2255E 03	0.0						
			0.0	0.1640E-04	0.1880E 02	0.0	0.9400E 02	0.0	0.1128E 03	0.1370E-04
			0.1315E 03	0.5350E-04	0.1503E 03	0.9250E-04	0.1691E 03	0.1070E-03	0.1879E 03	0.9250E-04
			0.2067E 03	0.5350E-04	0.2255E 03	0.1640E-04				
-1	0	0	0.0							
20	0	4	0.2255E 03	0.0						
			0.0	0.4790E-02	0.1880E 02	0.7250E-02	0.3760E 02	0.5400E-02	0.5640E 02	0.1370E-02
			0.7520E 02	0.0	0.1503E 03	0.0	0.1691E 03	0.4770E-03	0.1879E 03	0.2020E-02
			0.2067E 03	0.3490E-02	0.2255E 03	0.4790E-02				
-1	0	0	0.0							
21	0	4	0.2255E 03	0.0						
			0.0	0.0	0.3760E 02	0.0	0.5640E 02	0.1380E-02	0.7520E 02	0.5120E-02
			0.9400E 02	0.6120E-02	0.1128E 03	0.4030E-02	0.1315E 03	0.3490E-02	0.1503E 03	0.2020E-02
			0.1691E 03	0.4870E-03	0.1879E 03	0.0	0.2255E 03	0.0		
-1	0	0	0.0							

```
22     0     4     0.2255E 03 0.0
                   0.0        0.5790E-03 0.1880E 02 0.3950E-02 0.3760E 02 0.8810E-02 0.5640E 02 0.1070E-01
                   0.7520E 02 0.8190E-02 0.9400E 02 0.3330E-02 0.1128E 03 0.4870E-03 0.1315E 03 0.0
                   0.2067E 03 0.0        0.2255E 03 0.5790E-03
-1     0     0     0.0

-1     0     0     0.0
```

END OF HEATING DATA

END OF PROBLEM INPUT

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

BEGINNING OF ORBIT PERIOD(MIN)

NODE NUMBER

TIME	T(1)	T(2)	T(3)	T(4)	T(5)	T(6)	T(7)	T(8)	T(9)	T(10)	TIME
$\boxed{0.0}$	55.00	55.00	54.44	53.89	54.44	53.89	54.44	53.89	54.44	53.89	0.0
10.00	55.01	55.00	54.44	53.94	54.42	53.92	54.41	53.91	54.41	53.91	10.00
20.00	55.01	55.00	54.47	53.97	54.43	53.93	54.41	53.91	54.43	53.93	20.00
30.00	55.01	55.00	54.50	54.00	54.44	53.94	54.42	53.92	54.46	53.96	30.00
40.00	55.01	55.00	54.52	54.02	54.45	53.95	54.43	53.93	54.50	54.00	40.00
49.99	55.01	55.00	54.54	54.03	54.46	53.96	54.45	53.95	54.54	54.04	49.99
59.99	55.02	55.01	54.54	54.04	54.48	53.97	54.48	53.98	54.58	54.08	59.99
69.99	55.02	55.01	54.55	54.05	54.49	53.99	54.51	54.01	54.61	54.10	69.99
79.99	55.02	55.01	54.56	54.05	54.51	54.01	54.55	54.05	54.62	54.12	79.99
89.99	55.02	55.01	54.57	54.06	54.53	54.03	54.58	54.08	54.63	54.13	89.99
99.99	55.02	55.01	54.58	54.07	54.55	54.04	54.60	54.10	54.63	54.13	99.99
109.99	55.03	55.02	54.58	54.07	54.56	54.06	54.61	54.11	54.63	54.12	109.99
119.98	55.03	55.02	54.59	54.08	54.57	54.07	54.62	54.11	54.62	54.11	119.98
129.98	55.03	55.02	54.59	54.08	54.58	54.07	54.62	54.12	54.61	54.11	129.98
139.98	55.03	55.02	54.59	54.08	54.59	54.08	54.63	54.12	54.61	54.11	139.98
149.98	55.03	55.02	54.59	54.08	54.60	54.09	54.63	54.12	54.61	54.10	149.98
159.98	55.04	55.03	54.60	54.09	54.61	54.10	54.63	54.13	54.61	54.10	159.98
169.98	55.04	55.03	54.60	54.09	54.62	54.11	54.63	54.13	54.61	54.10	169.98
179.97	55.04	55.03	54.61	54.10	54.63	54.12	54.63	54.13	54.61	54.10	179.97
189.97	55.04	55.03	54.61	54.10	54.64	54.13	54.63	54.12	54.61	54.10	189.97
199.97	55.04	55.04	54.62	54.11	54.65	54.14	54.63	54.12	54.61	54.10	199.97
209.97	55.05	55.04	54.63	54.12	54.65	54.14	54.63	54.12	54.61	54.10	209.97
219.97	55.05	55.04	54.65	54.14	54.66	54.15	54.63	54.12	54.62	54.11	219.97
$\boxed{225.53}$	55.05	55.04	54.66	54.14	54.66	54.15	54.63	54.12	54.62	54.11	225.53

END OF ~~ORBIT~~ PERIOD(MIN)

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(11)	T(12)	T(25)	T(26)	T(27)	T(28)	T(29)	T(30)	T(31)	T(32)	TIME
0.0	60.56	52.78	17.50	17.50	17.50	16.00	16.00	16.00	15.78	17.72	0.0
10.00	60.61	52.74	17.26	17.26	17.26	15.79	15.79	15.79	15.55	17.49	10.00
20.00	60.64	52.73	17.04	17.04	17.04	15.57	15.57	15.57	15.33	17.28	20.00
30.00	60.67	52.73	16.85	16.85	16.85	15.37	15.37	15.37	15.14	17.08	30.00
40.00	60.70	52.75	16.68	16.68	16.68	15.20	15.20	15.20	14.96	16.91	40.00
49.99	60.72	52.77	16.55	16.55	16.55	15.07	15.07	15.07	14.83	16.78	49.99
59.99	60.75	52.79	16.45	16.45	16.45	14.96	14.96	14.96	14.73	16.67	59.99
69.99	60.77	52.81	16.39	16.39	16.39	14.90	14.90	14.90	14.66	16.60	69.99
79.99	60.79	52.83	16.35	16.35	16.35	14.86	14.86	14.86	14.62	16.56	79.99
89.99	60.81	52.84	16.36	16.36	16.36	14.87	14.87	14.87	14.63	16.57	89.99
99.99	60.83	52.85	16.41	16.41	16.41	14.91	14.91	14.91	14.67	16.61	99.99
109.99	60.84	52.85	16.50	16.50	16.50	15.01	15.01	15.01	14.78	16.70	109.99
119.98	60.85	52.86	16.65	16.65	16.65	15.16	15.16	15.16	14.93	16.84	119.98
129.98	60.86	52.86	16.86	16.86	16.86	15.37	15.37	15.37	15.14	17.04	129.98
139.98	60.87	52.86	17.10	17.10	17.10	15.62	15.62	15.62	15.38	17.27	139.98
149.98	60.88	52.86	17.37	17.37	17.37	15.89	15.89	15.89	15.65	17.54	149.98
159.98	60.89	52.86	17.62	17.62	17.62	16.15	16.15	16.15	15.91	17.79	159.98
169.98	60.90	52.86	17.85	17.85	17.85	16.38	16.38	16.38	16.14	18.02	169.98
179.97	60.91	52.86	18.00	18.00	18.00	16.54	16.54	16.54	16.30	18.19	179.97
189.97	60.91	52.86	18.08	18.08	18.08	16.62	16.62	16.62	16.38	18.28	189.97
199.97	60.92	52.86	18.07	18.07	18.07	16.60	16.60	16.60	16.37	18.28	199.97
209.97	60.93	52.86	17.98	17.98	17.98	16.51	16.51	16.51	16.28	18.20	209.97
219.97	60.93	52.86	17.82	17.82	17.82	16.35	16.35	16.35	16.12	18.05	219.97
225.53	60.94	52.87	17.71	17.71	17.71	16.24	16.24	16.24	16.00	17.94	225.53

BENDIX AEROSPACE SYSTEMS DIVISION | THERMOPHYSICS GROUP | ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(33)	T(34)	T(35)	T(36)	T(37)	T(38)	T(39)	T(40)	T(41)	T(42)	TIME
0.0	17.72	17.72	17.22	17.22	17.22	17.22	17.78	17.78	17.78	18.33	0.0
10.00	17.49	17.49	17.02	17.02	17.02	17.00	17.56	17.56	17.56	18.10	10.00
20.00	17.28	17.28	16.81	16.81	16.81	16.78	17.35	17.35	17.35	17.89	20.00
30.00	17.08	17.08	16.61	16.61	16.61	16.59	17.15	17.15	17.15	17.69	30.00
40.00	16.91	16.91	16.44	16.44	16.44	16.42	16.98	16.98	16.98	17.52	40.00
49.99	16.78	16.78	16.30	16.30	16.30	16.28	16.84	16.84	16.84	17.38	49.99
59.99	16.67	16.67	16.19	16.19	16.19	16.17	16.74	16.74	16.74	17.28	59.99
69.99	16.60	16.60	16.12	16.12	16.12	16.10	16.67	16.67	16.67	17.21	69.99
79.99	16.56	16.56	16.08	16.08	16.08	16.06	16.63	16.63	16.63	17.16	79.99
89.99	16.57	16.57	16.08	16.08	16.08	16.06	16.63	16.63	16.63	17.16	89.99
99.99	16.61	16.61	16.12	16.12	16.12	16.10	16.66	16.66	16.66	17.20	99.99
109.99	16.70	16.70	16.21	16.21	16.21	16.19	16.75	16.75	16.75	17.28	109.99
119.98	16.84	16.84	16.36	16.36	16.36	16.33	16.89	16.89	16.89	17.42	119.98
129.98	17.04	17.04	16.55	16.55	16.55	16.53	17.08	17.08	17.08	17.61	129.98
139.98	17.27	17.27	16.79	16.79	16.79	16.77	17.32	17.32	17.32	17.84	139.98
149.98	17.54	17.54	17.05	17.05	17.05	17.03	17.58	17.58	17.58	18.10	149.98
159.98	17.79	17.79	17.31	17.31	17.31	17.29	17.84	17.84	17.84	18.35	159.98
169.98	18.02	18.02	17.54	17.54	17.54	17.52	18.07	18.07	18.07	18.58	169.98
179.97	18.19	18.19	17.71	17.71	17.71	17.69	18.24	18.24	18.24	18.76	179.97
189.97	18.28	18.28	17.81	17.81	17.81	17.78	18.33	18.33	18.33	18.85	189.97
199.97	18.28	18.28	17.81	17.81	17.81	17.78	18.34	18.34	18.34	18.86	199.97
209.97	18.20	18.20	17.73	17.73	17.73	17.70	18.26	18.26	18.26	18.79	209.97
219.97	18.05	18.05	17.58	17.58	17.58	17.56	18.12	18.12	18.12	18.65	219.97
225.53	17.94	17.94	17.47	17.47	17.47	17.45	18.01	18.01	18.01	18.55	225.53

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION
THERMOPHYSICS GROUP
ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN   RUN NUMBER   RUN DATE 08/27/74   RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(43)	T(44)	T(45)	T(46)	T(47)	T(48)	T(49)	T(50)	T(51)	T(52)	TIME
0.0	66.67	66.11	66.11	66.11	60.56	60.56	60.56	9.78	9.78	9.78	0.0
10.00	66.34	66.30	66.30	66.30	60.54	60.54	60.54	9.99	9.99	9.99	10.00
20.00	66.40	66.26	66.26	66.26	60.57	60.57	60.57	10.05	10.05	10.05	20.00
30.00	66.59	66.15	66.15	66.15	60.60	60.60	60.60	9.95	9.95	9.95	30.00
40.00	66.54	66.11	66.11	66.11	60.63	60.63	60.63	9.70	9.70	9.70	40.00
49.99	66.30	66.15	66.15	66.15	60.65	60.65	60.65	9.33	9.33	9.33	49.99
59.99	66.53	66.03	66.03	66.03	60.67	60.67	60.67	8.89	8.89	8.89	59.99
69.99	66.48	66.03	66.03	66.03	60.70	60.70	60.70	8.49	8.49	8.49	69.99
79.99	66.36	66.06	66.06	66.06	60.72	60.72	60.72	8.14	8.14	8.14	79.99
89.99	66.10	66.16	66.16	66.16	60.74	60.74	60.74	7.89	7.89	7.89	89.99
99.99	66.36	66.08	66.08	66.08	60.75	60.75	60.75	7.72	7.72	7.72	99.99
109.99	66.24	66.16	66.16	66.16	60.77	60.77	60.77	7.62	7.62	7.62	109.99
119.98	66.51	66.12	66.12	66.12	60.78	60.78	60.78	7.59	7.59	7.59	119.98
129.98	66.30	66.27	66.27	66.27	60.79	60.79	60.79	7.60	7.60	7.60	129.98
139.98	66.50	66.29	66.29	66.29	60.80	60.80	60.80	7.66	7.66	7.66	139.98
149.98	66.52	66.38	66.38	66.38	60.81	60.81	60.81	7.75	7.75	7.75	149.98
159.98	66.56	66.48	66.48	66.48	60.82	60.82	60.82	7.88	7.88	7.88	159.98
169.98	66.79	66.50	66.50	66.50	60.83	60.83	60.83	8.05	8.05	8.05	169.98
179.97	66.85	66.56	66.56	66.56	60.84	60.84	60.84	8.31	8.31	8.31	179.97
189.97	66.92	66.63	66.63	66.63	60.85	60.85	60.85	8.67	8.67	8.67	189.97
199.97	66.94	66.66	66.66	66.66	60.86	60.86	60.86	9.07	9.07	9.07	199.97
209.97	66.98	66.61	66.61	66.61	60.86	60.86	60.86	9.50	9.50	9.50	209.97
219.97	66.71	66.67	66.67	66.67	60.87	60.87	60.87	9.85	9.85	9.85	219.97
225.53	66.71	66.63	66.63	66.63	60.87	60.87	60.87	10.01	10.01	10.01	225.53

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(53)	T(54)	T(55)	T(56)	T(57)	T(58)	T(59)	T(60)	T(61)	T(62)	TIME
0.0	8.50	8.50	8.50	8.28	9.94	9.94	9.94	9.50	9.50	9.50	0.0
10.00	8.72	8.72	8.72	8.51	10.17	10.17	10.17	9.75	9.75	9.75	10.00
20.00	8.78	8.78	8.78	8.58	10.25	10.25	10.25	9.83	9.83	9.83	20.00
30.00	8.68	8.68	8.68	8.47	10.17	10.17	10.17	9.76	9.76	9.76	30.00
40.00	8.42	8.42	8.42	8.22	9.94	9.94	9.94	9.52	9.52	9.52	40.00
49.99	8.05	8.05	8.05	7.84	9.59	9.59	9.59	9.17	9.17	9.17	49.99
59.99	7.60	7.60	7.60	7.39	9.15	9.15	9.15	8.74	8.74	8.74	59.99
69.99	7.19	7.19	7.19	6.98	8.74	8.74	8.74	8.33	8.33	8.33	69.99
79.99	6.84	6.84	6.84	6.63	8.39	8.39	8.39	7.97	7.97	7.97	79.99
89.99	6.58	6.58	6.58	6.37	8.13	8.13	8.13	7.70	7.70	7.70	89.99
99.99	6.41	6.41	6.41	6.20	7.95	7.95	7.95	7.52	7.52	7.52	99.99
109.99	6.31	6.31	6.31	6.10	7.84	7.84	7.84	7.41	7.41	7.41	109.99
119.98	6.27	6.27	6.27	6.06	7.80	7.80	7.80	7.36	7.36	7.36	119.98
129.98	6.29	6.29	6.29	6.08	7.81	7.81	7.81	7.37	7.37	7.37	129.98
139.98	6.35	6.35	6.35	6.14	7.86	7.86	7.86	7.43	7.43	7.43	139.98
149.98	6.44	6.44	6.44	6.23	7.94	7.94	7.94	7.51	7.51	7.51	149.98
159.98	6.56	6.56	6.56	6.35	8.06	8.06	8.06	7.63	7.63	7.63	159.98
169.98	6.74	6.74	6.74	6.53	8.23	8.23	8.23	7.79	7.79	7.79	169.98
179.97	7.00	7.00	7.00	6.80	8.47	8.47	8.47	8.04	8.04	8.04	179.97
189.97	7.37	7.37	7.37	7.16	8.82	8.82	8.82	8.38	8.38	8.38	189.97
199.97	7.78	7.78	7.78	7.57	9.22	9.22	9.22	8.78	8.78	8.78	199.97
209.97	8.21	8.21	8.21	8.00	9.64	9.64	9.64	9.21	9.21	9.21	209.97
219.97	8.57	8.57	8.57	8.36	10.00	10.00	10.00	9.58	9.58	9.58	219.97
225.53	8.73	8.73	8.73	8.53	10.17	10.17	10.17	9.75	9.75	9.75	225.53

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(63)	T(64)	T(65)	T(66)	T(67)	T(68)	T(69)	T(70)	T(71)	T(72)	TIME
0.0	9.50	10.00	10.00	10.00	10.44	53.89	53.89	53.89	53.89	54.44	0.0
10.00	9.72	10.22	10.22	10.22	10.71	54.13	53.86	53.86	53.86	54.34	10.00
20.00	9.81	10.31	10.31	10.31	10.80	54.14	53.92	53.92	53.92	54.37	20.00
30.00	9.74	10.25	10.25	10.25	10.75	54.04	53.98	53.98	53.98	54.40	30.00
40.00	9.50	10.02	10.02	10.02	10.53	54.02	53.95	53.95	53.95	54.42	40.00
49.99	9.15	9.68	9.68	9.68	10.19	54.07	53.85	53.85	53.85	54.44	49.99
59.99	8.72	9.25	9.25	9.25	9.77	53.84	53.80	53.80	53.80	54.44	59.99
69.99	8.31	8.84	8.84	8.84	9.36	53.75	53.69	53.69	53.69	54.45	69.99
79.99	7.95	8.48	8.48	8.48	9.00	53.70	53.57	53.57	53.57	54.46	79.99
89.99	7.68	8.21	8.21	8.21	8.73	53.73	53.43	53.43	53.43	54.46	89.99
99.99	7.50	8.03	8.03	8.03	8.55	53.56	53.41	53.41	53.41	54.47	99.99
109.99	7.39	7.92	7.92	7.92	8.43	53.58	53.34	53.34	53.34	54.48	109.99
119.98	7.34	7.87	7.87	7.87	8.38	53.45	53.35	53.35	53.35	54.48	119.98
129.98	7.35	7.87	7.87	7.87	8.39	53.56	53.30	53.30	53.30	54.48	129.98
139.98	7.40	7.92	7.92	7.92	8.44	53.51	53.33	53.33	53.33	54.49	139.98
149.98	7.49	8.01	8.01	8.01	8.52	53.55	53.34	53.34	53.34	54.49	149.98
159.98	7.61	8.12	8.12	8.12	8.63	53.59	53.36	53.36	53.36	54.49	159.98
169.98	7.77	8.28	8.28	8.28	8.79	53.57	53.42	53.42	53.42	54.50	169.98
179.97	8.02	8.52	8.52	8.52	9.02	53.63	53.48	53.48	53.48	54.50	179.97
189.97	8.36	8.86	8.86	8.86	9.35	53.73	53.55	53.55	53.55	54.51	189.97
199.97	8.76	9.26	9.26	9.26	9.74	53.84	53.66	53.66	53.66	54.52	199.97
209.97	9.19	9.68	9.68	9.68	10.16	53.92	53.80	53.80	53.80	54.53	209.97
219.97	9.55	10.05	10.05	10.05	10.53	54.12	53.88	53.88	53.88	54.55	219.97
225.53	9.72	10.22	10.22	10.22	10.70	54.17	53.94	53.94	53.94	54.56	225.53

BENDIX AEROSPACE SYSTEMS DIVISION
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74

THERMOPHYSICS GROUP
RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

ANN ARBOR, MICHIGAN

TEMPERATURES IN DEGREES C

TIME	T(73)	T(74)	T(75)	T(76)	T(77)	T(78)	T(79)	T(80)	T(81)	T(82)	TIME
0.0	54.44	54.44	-6.44	-6.44	-6.44	-7.56	-7.56	-7.56	-7.72	-6.22	0.0
10.00	54.34	54.34	-6.25	-6.25	-6.25	-7.37	-7.37	-7.37	-7.55	-6.05	10.00
20.00	54.37	54.37	-6.01	-6.01	-6.01	-7.12	-7.12	-7.12	-7.30	-5.81	20.00
30.00	54.40	54.40	-5.72	-5.72	-5.72	-6.83	-6.83	-6.83	-7.01	-5.53	30.00
40.00	54.42	54.42	-5.40	-5.40	-5.40	-6.51	-6.51	-6.51	-6.69	-5.22	40.00
49.99	54.44	54.44	-5.10	-5.10	-5.10	-6.20	-6.20	-6.20	-6.38	-4.91	49.99
59.99	54.44	54.44	-4.83	-4.83	-4.83	-5.93	-5.93	-5.93	-6.11	-4.64	59.99
69.99	54.45	54.45	-4.64	-4.64	-4.64	-5.74	-5.74	-5.74	-5.91	-4.43	69.99
79.99	54.46	54.46	-4.54	-4.54	-4.54	-5.63	-5.63	-5.63	-5.80	-4.32	79.99
89.99	54.46	54.46	-4.54	-4.54	-4.54	-5.63	-5.63	-5.63	-5.80	-4.30	89.99
99.99	54.47	54.47	-4.63	-4.63	-4.63	-5.72	-5.72	-5.72	-5.90	-4.38	99.99
109.99	54.48	54.48	-4.80	-4.80	-4.80	-5.89	-5.89	-5.89	-6.07	-4.54	109.99
119.98	54.48	54.48	-5.02	-5.02	-5.02	-6.11	-6.11	-6.11	-6.29	-4.75	119.98
129.98	54.48	54.48	-5.26	-5.26	-5.26	-6.36	-6.36	-6.36	-6.53	-4.99	129.98
139.98	54.49	54.49	-5.50	-5.50	-5.50	-6.60	-6.60	-6.60	-6.78	-5.23	139.98
149.98	54.49	54.49	-5.71	-5.71	-5.71	-6.82	-6.82	-6.82	-7.00	-5.45	149.98
159.98	54.49	54.49	-5.90	-5.90	-5.90	-7.01	-7.01	-7.01	-7.19	-5.65	159.98
169.98	54.50	54.50	-6.06	-6.06	-6.06	-7.17	-7.17	-7.17	-7.35	-5.81	169.98
179.97	54.50	54.50	-6.18	-6.18	-6.18	-7.29	-7.29	-7.29	-7.47	-5.93	179.97
189.97	54.51	54.51	-6.27	-6.27	-6.27	-7.38	-7.38	-7.38	-7.56	-6.02	189.97
199.97	54.52	54.52	-6.31	-6.31	-6.31	-7.43	-7.43	-7.43	-7.60	-6.07	199.97
209.97	54.53	54.53	-6.31	-6.31	-6.31	-7.43	-7.43	-7.43	-7.61	-6.08	209.97
219.97	54.55	54.55	-6.25	-6.25	-6.25	-7.37	-7.37	-7.37	-7.54	-6.02	219.97
225.53	54.56	54.56	-6.19	-6.19	-6.19	-7.31	-7.31	-7.31	-7.49	-5.97	225.53

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION — THERMOPHYSICS GROUP — ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(83)	T(84)	T(85)	T(86)	T(87)	T(88)	T(89)	T(90)	T(91)	T(92)	TIME
0.0	-6.22	-6.22	-6.61	-6.61	-6.61	-6.67	-6.11	-6.11	-6.11	-5.61	0.0
10.00	-6.05	-6.05	-6.45	-6.45	-6.45	-6.47	-5.96	-5.96	-5.96	-5.41	10.00
20.00	-5.81	-5.81	-6.21	-6.21	-6.21	-6.23	-5.73	-5.73	-5.73	-5.18	20.00
30.00	-5.53	-5.53	-5.93	-5.93	-5.93	-5.95	-5.45	-5.45	-5.45	-4.91	30.00
40.00	-5.22	-5.22	-5.62	-5.62	-5.62	-5.64	-5.14	-5.14	-5.14	-4.60	40.00
49.99	-4.91	-4.91	-5.31	-5.31	-5.31	-5.33	-4.83	-4.83	-4.83	-4.29	49.99
59.99	-4.64	-4.64	-5.03	-5.03	-5.03	-5.05	-4.55	-4.55	-4.55	-4.01	59.99
69.99	-4.43	-4.43	-4.83	-4.83	-4.83	-4.85	-4.35	-4.35	-4.35	-3.80	69.99
79.99	-4.32	-4.32	-4.71	-4.71	-4.71	-4.73	-4.22	-4.22	-4.22	-3.68	79.99
89.99	-4.30	-4.30	-4.69	-4.69	-4.69	-4.71	-4.20	-4.20	-4.20	-3.65	89.99
99.99	-4.38	-4.38	-4.77	-4.77	-4.77	-4.79	-4.28	-4.28	-4.28	-3.72	99.99
109.99	-4.54	-4.54	-4.93	-4.93	-4.93	-4.94	-4.43	-4.43	-4.43	-3.87	109.99
119.98	-4.75	-4.75	-5.14	-5.14	-5.14	-5.16	-4.64	-4.64	-4.64	-4.08	119.98
129.98	-4.99	-4.99	-5.38	-5.38	-5.38	-5.39	-4.88	-4.88	-4.88	-4.31	129.98
139.98	-5.23	-5.23	-5.62	-5.62	-5.62	-5.64	-5.12	-5.12	-5.12	-4.55	139.98
149.98	-5.45	-5.45	-5.84	-5.84	-5.84	-5.86	-5.34	-5.34	-5.34	-4.77	149.98
159.98	-5.65	-5.65	-6.04	-6.04	-6.04	-6.05	-5.53	-5.53	-5.53	-4.97	159.98
169.98	-5.81	-5.81	-6.20	-6.20	-6.20	-6.22	-5.70	-5.70	-5.70	-5.13	169.98
179.97	-5.93	-5.93	-6.33	-6.33	-6.33	-6.34	-5.82	-5.82	-5.82	-5.26	179.97
189.97	-6.02	-6.02	-6.42	-6.42	-6.42	-6.44	-5.92	-5.92	-5.92	-5.35	189.97
199.97	-6.07	-6.07	-6.47	-6.47	-6.47	-6.49	-5.97	-5.97	-5.97	-5.41	199.97
209.97	-6.08	-6.08	-6.48	-6.48	-6.48	-6.49	-5.98	-5.98	-5.98	-5.42	209.97
219.97	-6.02	-6.02	-6.42	-6.42	-6.42	-6.44	-5.93	-5.93	-5.93	-5.37	219.97
225.53	-5.97	-5.97	-6.37	-6.37	-6.37	-6.39	-5.88	-5.88	-5.88	-5.32	225.53

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(93)	T(94)	T(95)	T(96)	T(97)	T(98)	T(99)	T(100)	T(101)	T(102)	TIME
0.0	29.67	29.67	29.67	29.67	52.22	52.22	52.22	-1.56	-1.56	-1.56	0.0
10.00	29.79	29.82	29.82	29.82	52.51	52.51	52.51	-2.27	-2.27	-2.27	10.00
20.00	29.91	29.92	29.92	29.92	52.50	52.50	52.50	-2.95	-2.95	-2.95	20.00
30.00	30.02	30.03	30.03	30.03	52.50	52.50	52.50	-3.50	-3.50	-3.50	30.00
40.00	30.15	30.15	30.15	30.15	52.51	52.51	52.51	-3.94	-3.94	-3.94	40.00
49.99	30.26	30.28	30.28	30.28	52.53	52.53	52.53	-4.28	-4.28	-4.28	49.99
59.99	30.39	30.38	30.38	30.38	52.56	52.56	52.56	-4.54	-4.54	-4.54	59.99
69.99	30.45	30.46	30.46	30.46	52.58	52.58	52.58	-4.75	-4.75	-4.75	69.99
79.99	30.49	30.51	30.51	30.51	52.60	52.60	52.60	-4.91	-4.91	-4.91	79.99
89.99	30.49	30.51	30.51	30.51	52.61	52.61	52.61	-5.03	-5.03	-5.03	89.99
99.99	30.47	30.48	30.48	30.48	52.62	52.62	52.62	-5.10	-5.10	-5.10	99.99
109.99	30.41	30.43	30.43	30.43	52.62	52.62	52.62	-5.04	-5.04	-5.04	109.99
119.98	30.35	30.36	30.36	30.36	52.62	52.62	52.62	-4.80	-4.80	-4.80	119.98
129.98	30.27	30.29	30.29	30.29	52.62	52.62	52.62	-4.28	-4.28	-4.28	129.98
139.98	30.20	30.22	30.22	30.22	52.62	52.62	52.62	-3.55	-3.55	-3.55	139.98
149.98	30.14	30.15	30.15	30.15	52.62	52.62	52.62	-2.64	-2.64	-2.64	149.98
159.98	30.07	30.09	30.09	30.09	52.62	52.62	52.62	-1.73	-1.73	-1.73	159.98
169.98	30.02	30.04	30.04	30.04	52.62	52.62	52.62	-0.90	-0.90	-0.90	169.98
179.97	29.98	30.00	30.00	30.00	52.62	52.62	52.62	-0.30	-0.30	-0.30	179.97
189.97	29.95	29.96	29.96	29.96	52.62	52.62	52.62	0.04	0.04	0.04	189.97
199.97	29.93	29.94	29.94	29.94	52.62	52.62	52.62	0.03	0.03	0.03	199.97
209.97	29.92	29.94	29.94	29.94	52.62	52.62	52.62	-0.30	-0.30	-0.30	209.97
219.97	29.93	29.94	29.94	29.94	52.63	52.63	52.63	-0.88	-0.88	-0.88	219.97
225.53	29.94	29.96	29.96	29.96	52.63	52.63	52.63	-1.29	-1.29	-1.29	225.53

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(103)	T(104)	T(105)	T(106)	T(107)	T(108)	T(109)	T(110)	T(111)	T(112)	TIME
0.0	-2.61	-2.61	-2.61	-2.78	-1.22	-1.22	-1.22	-1.56	-1.56	-1.56	0.0
10.00	-3.36	-3.36	-3.36	-3.53	-1.94	-1.94	-1.94	-2.32	-2.32	-2.32	10.00
20.00	-4.05	-4.05	-4.05	-4.22	-2.62	-2.62	-2.62	-3.00	-3.00	-3.00	20.00
30.00	-4.61	-4.61	-4.61	-4.79	-3.20	-3.20	-3.20	-3.58	-3.58	-3.58	30.00
40.00	-5.06	-5.06	-5.06	-5.23	-3.65	-3.65	-3.65	-4.04	-4.04	-4.04	40.00
49.99	-5.40	-5.40	-5.40	-5.58	-4.00	-4.00	-4.00	-4.39	-4.39	-4.39	49.99
59.99	-5.67	-5.67	-5.67	-5.85	-4.27	-4.27	-4.27	-4.67	-4.67	-4.67	59.99
69.99	-5.88	-5.88	-5.88	-6.06	-4.48	-4.48	-4.48	-4.88	-4.88	-4.88	69.99
79.99	-6.04	-6.04	-6.04	-6.23	-4.65	-4.65	-4.65	-5.05	-5.05	-5.05	79.99
89.99	-6.17	-6.17	-6.17	-6.35	-4.78	-4.78	-4.78	-5.18	-5.18	-5.18	89.99
99.99	-6.24	-6.24	-6.24	-6.42	-4.86	-4.86	-4.86	-5.26	-5.26	-5.26	99.99
109.99	-6.18	-6.18	-6.18	-6.36	-4.81	-4.81	-4.81	-5.22	-5.22	-5.22	109.99
119.98	-5.94	-5.94	-5.94	-6.12	-4.61	-4.61	-4.61	-5.02	-5.02	-5.02	119.98
129.98	-5.42	-5.42	-5.42	-5.60	-4.13	-4.13	-4.13	-4.54	-4.54	-4.54	129.98
139.98	-4.67	-4.67	-4.67	-4.85	-3.42	-3.42	-3.42	-3.84	-3.84	-3.84	139.98
149.98	-3.75	-3.75	-3.75	-3.93	-2.54	-2.54	-2.54	-2.95	-2.95	-2.95	149.98
159.98	-2.83	-2.83	-2.83	-3.00	-1.62	-1.62	-1.62	-2.03	-2.03	-2.03	159.98
169.98	-1.98	-1.98	-1.98	-2.16	-0.78	-0.78	-0.78	-1.18	-1.18	-1.18	169.98
179.97	-1.37	-1.37	-1.37	-1.54	-0.14	-0.14	-0.14	-0.53	-0.53	-0.53	179.97
189.97	-1.02	-1.02	-1.02	-1.19	0.24	0.24	0.24	-0.15	-0.15	-0.15	189.97
199.97	-1.03	-1.03	-1.03	-1.20	0.28	0.28	0.28	-0.10	-0.10	-0.10	199.97
209.97	-1.36	-1.36	-1.36	-1.53	-0.01	-0.01	-0.01	-0.38	-0.38	-0.38	209.97
219.97	-1.95	-1.95	-1.95	-2.12	-0.56	-0.56	-0.56	-0.93	-0.93	-0.93	219.97
225.53	-2.37	-2.37	-2.37	-2.54	-0.96	-0.96	-0.96	-1.33	-1.33	-1.33	225.53

BENDIX AEROSPACE SYSTEMS DIVISION
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74

THERMOPHYSICS GROUP
RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

ANN ARBOR, MICHIGAN

TEMPERATURES IN DEGREES C

TIME	T(113)	T(114)	T(115)	T(116)	T(117)	T(118)	T(119)	T(120)	T(121)	T(122)	TIME
0.0	-1.61	-1.06	-1.06	-1.06	-0.50	32.33	32.33	32.33	32.33	53.89	0.0
10.00	-2.33	-1.79	-1.79	-1.79	-1.21	32.14	32.16	32.16	32.16	54.19	10.00
20.00	-3.01	-2.47	-2.47	-2.47	-1.89	31.95	31.97	31.97	31.97	54.20	20.00
30.00	-3.60	-3.06	-3.06	-3.06	-2.48	31.78	31.78	31.78	31.78	54.20	30.00
40.00	-4.05	-3.52	-3.52	-3.52	-2.94	31.63	31.64	31.64	31.64	54.21	40.00
49.99	-4.41	-3.87	-3.87	-3.87	-3.29	31.51	31.52	31.52	31.52	54.23	49.99
59.99	-4.69	-4.15	-4.15	-4.15	-3.57	31.42	31.43	31.43	31.43	54.24	59.99
69.99	-4.90	-4.37	-4.37	-4.37	-3.79	31.36	31.37	31.37	31.37	54.25	69.99
79.99	-5.07	-4.54	-4.54	-4.54	-3.96	31.30	31.32	31.32	31.32	54.27	79.99
89.99	-5.20	-4.67	-4.67	-4.67	-4.09	31.26	31.28	31.28	31.28	54.29	89.99
99.99	-5.28	-4.75	-4.75	-4.75	-4.17	31.25	31.26	31.26	31.26	54.31	99.99
109.99	-5.24	-4.72	-4.72	-4.72	-4.14	31.25	31.27	31.27	31.27	54.32	109.99
119.98	-5.04	-4.53	-4.53	-4.53	-3.97	31.30	31.31	31.31	31.31	54.33	119.98
129.98	-4.57	-4.07	-4.07	-4.07	-3.52	31.41	31.43	31.43	31.43	54.34	129.98
139.98	-3.85	-3.37	-3.37	-3.37	-2.84	31.60	31.61	31.61	31.61	54.35	139.98
149.98	-2.98	-2.50	-2.50	-2.50	-1.98	31.84	31.85	31.85	31.85	54.37	149.98
159.98	-2.05	-1.58	-1.58	-1.58	-1.06	32.11	32.13	32.13	32.13	54.38	159.98
169.98	-1.21	-0.74	-0.74	-0.74	-0.22	32.38	32.39	32.39	32.39	54.39	169.98
179.97	-0.55	-0.08	-0.08	-0.08	0.44	32.61	32.62	32.62	32.62	54.41	179.97
139.97	-0.17	0.32	0.32	0.32	0.85	32.76	32.78	32.78	32.78	54.42	189.97
199.97	-0.11	0.38	0.38	0.38	0.93	32.83	32.85	32.85	32.85	54.42	199.97
209.97	-0.40	0.12	0.12	0.12	0.67	32.80	32.81	32.81	32.81	54.43	209.97
219.97	-0.94	-0.42	-0.42	-0.42	0.15	32.68	32.69	32.69	32.69	54.43	219.97
225.53	-1.34	-0.81	-0.81	-0.81	-0.23	32.58	32.59	32.59	32.59	54.43	225.53

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(123)	T(124)	T(125)	T(126)	T(127)	T(128)	T(129)	T(130)	T(131)	T(132)	TIME
0.0	53.89	53.89	17.22	-1.17	-1.56	-6.61	-4.72	-5.11	-5.44	-5.83	0.0
10.00	54.19	54.19	17.00	-0.45	-0.84	-6.43	-4.96	-5.35	-5.13	-5.52	10.00
20.00	54.20	54.20	16.78	-0.02	-0.40	-6.18	-5.15	-5.54	-4.54	-4.93	20.00
30.00	54.20	54.20	16.58	0.06	-0.32	-5.90	-5.30	-5.68	-3.74	-4.12	30.00
40.00	54.21	54.21	16.41	-0.72	-0.60	-5.58	-5.41	-5.79	-2.77	-3.15	40.00
49.99	54.23	54.23	16.28	-0.80	-1.18	-5.27	-5.40	-5.78	-1.83	-2.20	49.99
59.99	54.24	54.24	16.18	-1.60	-1.97	-5.00	-5.26	-5.64	-0.98	-1.35	59.99
69.99	54.25	54.25	16.11	-2.38	-2.75	-4.80	-4.82	-5.20	-0.39	-0.76	69.99
79.99	54.27	54.27	16.07	-3.09	-3.46	-4.69	-4.10	-4.47	-0.09	-0.45	79.99
89.99	54.29	54.29	16.07	-3.66	-4.03	-4.68	-3.17	-3.55	-0.16	-0.53	89.99
99.99	54.31	54.31	16.12	-4.10	-4.47	-4.77	-2.14	-2.51	-0.55	-0.92	99.99
109.99	54.32	54.32	16.22	-4.44	-4.82	-4.94	-1.20	-1.57	-1.20	-1.57	109.99
119.98	54.33	54.33	16.36	-4.71	-5.09	-5.16	-0.42	-0.79	-1.98	-2.35	119.98
129.98	54.34	54.34	16.57	-4.92	-5.30	-5.40	0.06	-0.31	-2.71	-3.08	129.98
139.98	54.35	54.35	16.81	-5.08	-5.47	-5.65	0.22	-0.15	-3.36	-3.72	139.98
149.98	54.37	54.37	17.08	-5.21	-5.60	-5.87	-0.00	-0.37	-3.86	-4.23	149.98
159.98	54.38	54.38	17.34	-5.26	-5.64	-6.06	-0.53	-0.89	-4.25	-4.62	159.98
169.98	54.39	54.39	17.57	-5.17	-5.56	-6.22	-1.30	-1.66	-4.56	-4.93	169.98
179.97	54.41	54.41	17.73	-4.84	-5.22	-6.35	-2.11	-2.48	-4.80	-5.17	179.97
189.97	54.42	54.42	17.81	-4.20	-4.59	-6.44	-2.85	-3.22	-4.99	-5.36	189.97
199.97	54.42	54.42	17.80	-3.35	-3.74	-6.48	-3.46	-3.83	-5.14	-5.51	199.97
209.97	54.43	54.43	17.71	-2.35	-2.74	-6.49	-3.94	-4.31	-5.25	-5.62	209.97
219.97	54.43	54.43	17.55	-1.40	-1.78	-6.43	-4.31	-4.68	-5.24	-5.62	219.97
225.53	54.43	54.43	17.45	-0.91	-1.29	-6.37	-4.48	-4.85	-5.18	-5.56	225.53

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(133)	T(134)	T(135)	T(136)	T(137)	T(138)	T(139)	T(140)	T(141)	T(142)	TIME
0.0	-1.72	-2.06	66.67	32.17	31.72	29.67	31.28	30.89	31.00	30.56	0.0
10.00	-2.46	-2.81	66.35	32.49	32.05	29.78	31.23	30.83	31.11	30.71	10.00
20.00	-3.15	-3.50	66.38	32.77	32.34	29.88	31.18	30.78	31.30	30.90	20.00
30.00	-3.73	-4.09	66.39	32.92	32.49	29.99	31.13	30.74	31.58	31.18	30.00
40.00	-4.17	-4.54	66.33	32.92	32.49	30.11	31.10	30.71	31.94	31.54	40.00
49.99	-4.52	-4.89	66.28	32.79	32.36	30.23	31.10	30.71	32.30	31.90	49.99
59.99	-4.79	-5.16	66.26	32.55	32.12	30.34	31.16	30.76	32.63	32.23	59.99
69.99	-5.00	-5.38	66.24	32.29	31.86	30.42	31.30	30.91	32.86	32.46	69.99
79.99	-5.16	-5.54	66.23	32.04	31.61	30.47	31.53	31.13	32.98	32.58	79.99
89.99	-5.29	-5.67	66.24	31.84	31.41	30.47	31.80	31.40	32.96	32.57	89.99
99.99	-5.36	-5.74	66.25	31.69	31.26	30.44	32.09	31.69	32.84	32.44	99.99
109.99	-5.30	-5.69	66.27	31.57	31.13	30.39	32.34	31.94	32.64	32.24	109.99
119.98	-5.08	-5.46	66.31	31.47	31.04	30.32	32.56	32.16	32.39	31.99	119.98
129.98	-4.57	-4.95	66.37	31.40	30.96	30.25	32.74	32.34	32.16	31.76	129.98
139.98	-3.83	-4.22	66.43	31.34	30.91	30.18	32.85	32.45	31.94	31.54	139.98
149.98	-2.93	-3.31	66.50	31.30	30.86	30.11	32.86	32.46	31.77	31.36	149.98
159.98	-1.99	-2.37	66.58	31.27	30.83	30.05	32.76	32.36	31.62	31.22	159.98
169.98	-1.14	-1.52	66.66	31.27	30.84	30.00	32.58	32.18	31.51	31.11	169.98
179.97	-0.50	-0.88	66.73	31.34	30.90	29.95	32.35	31.95	31.42	31.02	179.97
189.97	-0.14	-0.52	66.78	31.48	31.04	29.92	32.12	31.72	31.35	30.95	189.97
199.97	-0.13	-0.51	66.80	31.69	31.25	29.90	31.92	31.51	31.30	30.90	199.97
209.97	-0.45	-0.83	66.79	31.96	31.52	29.89	31.75	31.34	31.26	30.86	209.97
219.97	-1.03	-1.41	66.77	32.26	31.83	29.90	31.61	31.21	31.25	30.85	219.97
225.53	-1.45	-1.82	66.75	32.43	31.99	29.91	31.55	31.15	31.25	30.85	225.53

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(143)	T(144)	T(145)	T(146)	T(147)	T(148)	T(149)	T(150)	T(151)	T(152)	TIME
0.0	32.28	31.83	66.11	32.17	31.72	29.67	31.28	30.89	31.00	30.61	0.0
10.00	32.13	31.70	66.22	32.51	32.07	29.80	31.25	30.85	31.13	30.72	10.00
20.00	31.93	31.50	66.17	32.78	32.35	29.90	31.19	30.80	31.31	30.91	20.00
30.00	31.74	31.32	66.11	32.93	32.50	30.00	31.15	30.75	31.59	31.19	30.00
40.00	31.59	31.16	66.07	32.93	32.51	30.12	31.11	30.72	31.95	31.55	40.00
49.99	31.47	31.04	66.05	32.80	32.37	30.24	31.12	30.73	32.31	31.91	49.99
59.99	31.38	30.95	66.02	32.56	32.13	30.36	31.17	30.78	32.65	32.24	59.99
69.99	31.31	30.88	66.00	32.30	31.87	30.44	31.31	30.92	32.88	32.48	69.99
79.99	31.26	30.83	65.99	32.06	31.63	30.48	31.54	31.15	32.99	32.59	79.99
89.99	31.23	30.80	65.99	31.86	31.43	30.49	31.81	31.41	32.98	32.58	89.99
99.99	31.20	30.78	66.01	31.70	31.27	30.46	32.10	31.70	32.85	32.45	99.99
109.99	31.21	30.78	66.03	31.58	31.15	30.41	32.35	31.95	32.65	32.25	109.99
119.98	31.25	30.82	66.07	31.48	31.05	30.34	32.57	32.17	32.41	32.01	119.98
129.98	31.37	30.93	66.12	31.41	30.98	30.27	32.76	32.36	32.17	31.77	129.98
139.98	31.55	31.11	66.19	31.36	30.92	30.20	32.87	32.47	31.96	31.56	139.98
149.98	31.79	31.35	66.26	31.31	30.87	30.13	32.87	32.47	31.78	31.38	149.98
159.98	32.06	31.63	66.34	31.28	30.85	30.06	32.77	32.38	31.64	31.24	159.98
169.98	32.33	31.90	66.42	31.29	30.85	30.01	32.59	32.19	31.52	31.12	169.98
179.97	32.57	32.13	66.49	31.35	30.91	29.97	32.36	31.96	31.44	31.04	179.97
189.97	32.73	32.30	66.54	31.49	31.05	29.93	32.14	31.73	31.37	30.97	189.97
199.97	32.80	32.37	66.56	31.70	31.26	29.91	31.93	31.53	31.32	30.92	199.97
209.97	32.78	32.35	66.55	31.98	31.54	29.91	31.76	31.36	31.28	30.87	209.97
219.97	32.66	32.23	66.53	32.28	31.84	29.91	31.63	31.22	31.26	30.86	219.97
225.53	32.56	32.13	66.51	32.44	32.01	29.93	31.56	31.16	31.27	30.87	225.53

TEMPERATURE OUTPUT DATA

BENDIX AEROSPACE SYSTEMS DIVISION — THERMOPHYSICS GROUP — ANN ARBOR, MICHIGAN

PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(153)	T(154)	T(155)	T(156)	T(157)	T(158)	T(159)	T(160)	T(161)	T(162)	TIME
0.0	32.33	31.89	60.56	53.89	53.33	52.22	53.89	53.33	53.89	53.35	0.0
10.00	32.14	31.70	60.54	54.22	53.72	52.51	54.17	53.67	54.17	53.68	10.00
20.00	31.94	31.51	60.57	54.25	53.75	52.50	54.17	53.67	54.19	53.69	20.00
30.00	31.76	31.33	60.60	54.28	53.77	52.50	54.18	53.68	54.22	53.72	30.00
40.00	31.60	31.18	60.63	54.30	53.80	52.51	54.19	53.69	54.27	53.77	40.00
49.99	31.49	31.06	60.65	54.31	53.81	52.53	54.21	53.71	54.31	53.81	49.99
59.99	31.40	30.97	60.67	54.32	53.81	52.56	54.24	53.74	54.35	53.85	59.99
69.99	31.33	30.90	60.69	54.32	53.82	52.58	54.27	53.77	54.38	53.88	69.99
79.99	31.28	30.85	60.72	54.33	53.82	52.60	54.31	53.81	54.40	53.90	79.99
89.99	31.24	30.81	60.73	54.33	53.83	52.61	54.35	53.84	54.41	53.90	89.99
99.99	31.22	30.79	60.75	54.34	53.83	52.62	54.37	53.87	54.40	53.90	99.99
109.99	31.22	30.80	60.77	54.34	53.84	52.62	54.38	53.88	54.40	53.90	109.99
119.98	31.27	30.84	60.78	54.35	53.84	52.62	54.39	53.89	54.39	53.89	119.98
129.98	31.39	30.95	60.79	54.35	53.84	52.62	54.40	53.89	54.38	53.88	129.98
139.98	31.56	31.13	60.80	54.35	53.84	52.62	54.40	53.90	54.38	53.87	139.98
149.98	31.80	31.37	60.81	54.35	53.85	52.62	54.41	53.90	54.37	53.87	149.98
159.98	32.08	31.64	60.82	54.36	53.85	52.62	54.41	53.90	54.37	53.87	159.98
169.98	32.34	31.91	60.83	54.36	53.85	52.62	54.41	53.90	54.37	53.86	169.98
179.97	32.58	32.15	60.84	54.37	53.86	52.62	54.40	53.90	54.37	53.86	179.97
189.97	32.74	32.31	60.85	54.38	53.87	52.62	54.40	53.89	54.37	53.86	189.97
199.97	32.82	32.39	60.85	54.39	53.88	52.62	54.40	53.89	54.37	53.86	199.97
209.97	32.79	32.36	60.86	54.40	53.89	52.62	54.40	53.89	54.37	53.86	209.97
219.97	32.67	32.24	60.86	54.42	53.91	52.63	54.39	53.89	54.38	53.87	219.97
225.53	32.57	32.14	60.87	54.43	53.92	52.63	54.39	53.88	54.38	53.87	225.53

BENDIX AEROSPACE SYSTEMS DIVISION THERMOPHYSICS GROUP ANN ARBOR, MICHIGAN
PROGRAM FLIGHT RUN RUN NUMBER RUN DATE 08/27/74 RUN TITLE LAGEOS SATELLITE THERMAL ANALYSIS

TEMPERATURES IN DEGREES C

TIME	T(163)	T(164)	T(201)	T(202)	T(203)	T(204)	T(205)	T(206)	T(0)	T(0)	TIME
0.0	53.89	53.33	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	0.0
10.00	54.19	53.69	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	10.00
20.00	54.20	53.70	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	20.00
30.00	54.20	53.70	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	30.00
40.00	54.21	53.71	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	40.00
49.99	54.23	53.72	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	49.99
59.99	54.24	53.74	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	59.99
69.99	54.25	53.75	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	69.99
79.99	54.27	53.77	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	79.99
89.99	54.29	53.79	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	89.99
99.99	54.31	53.80	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	99.99
109.99	54.32	53.82	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	109.99
119.98	54.33	53.83	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	119.98
129.98	54.34	53.84	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	129.98
139.98	54.35	53.85	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	139.98
149.98	54.37	53.86	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	149.98
159.98	54.38	53.87	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	159.98
169.98	54.39	53.89	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	169.98
179.97	54.41	53.90	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	179.97
189.97	54.42	53.91	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	189.97
199.97	54.42	53.92	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	199.97
209.97	54.43	53.92	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	209.97
219.97	54.43	53.92	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	219.97
225.53	54.43	53.92	-273.33	-273.33	-273.33	-273.33	-273.33	-273.33	0.0	0.0	225.53

*** RUN TERMINATED AT END OF DATA ***

Bendix
Aerospace
Systems Division

APPENDIX L

LAGEOS PHASE B

THERMAL/OPTICAL/VIBRATIONAL ANALYSIS AND TEST PROGRAM

FINAL PRESENTATION
NASA-MSFC LAGEOS PDR

SEPTEMBER 4, 1974

BENDIX PHASE B LAGEOS

THERMAL/OPTICAL/VIBRATION ANALYSIS AND TEST PROGRAM

OVERALL OBJECTIVE

VERIFY, THROUGH ANALYSIS AND TEST, THAT MSFC LAGEOS DESIGN PROVIDES A THERMAL ENVIRONMENT WHICH MAINTAINS ACCEPTABLE RETROREFLECTOR GRADIENTS (I. E., $<$ 50% DEGRATION FROM ISOTHERMAL PERFORMANCE).

SPECIFIC OBJECTIVES

- DEVELOP LAGEOS THERMAL MODEL AND CONDUCT THERMAL ANALYSIS TO PREDICT RETROREFLECTOR THERMAL BEHAVIOR.
- PREDICT OPTICAL PERFORMANCE UNDER VARIOUS THERMAL CONDITIONS.
- PROCURE AND FABRICATE TEST HARDWARE REQUIRED TO REPRESENT LAGEOS DESIGN FOR PURPOSES OF ENVIRONMENTAL TESTS.
- ACCOMPLISH THERMAL, OPTICAL AND MECHANICAL VIBRATION TESTS TO VERIFY THAT THERMAL MODEL AND THERMAL ANALYSIS PREDICTIONS ARE REPRESENTATIVE OF SATELLITE PERFORMANCE.

LAGEOS

BENDIX PDR PRESENTATIONS

THERMAL SESSION

THERMAL PARAMETRIC AND SATELLITE ANALYSIS

THERMAL/VACUUM TESTS

OPTICAL SESSION

THERMAL/OPTICAL ANALYSIS

THERMAL/OPTICAL TESTS

DYNAMICS SESSION

VIBRATION TESTS

ACOUSTICS

Bendix
Aerospace
Systems Division

LAGEOS

THERMAL DESIGN, TEST AND ANALYSIS

4 September 1974

LAGEOS

THERMAL DESIGN/ANALYSIS/TEST OUTLINE

- RATIONALE FOR TEST ITEM THERMAL DESIGN
- PRETEST THERMAL PREDICTIONS FOR TEST ITEM
- THERMAL/VACUUM TEST RESULTS
- CORRELATION OF ANALYSIS/TEST DATA
- SATELLITE THERMAL PERFORMANCE PREDICTIONS
- CONCLUSIONS AND RECOMMENDATIONS

LAGEOS

THERMAL DESIGN, TEST AND ANALYSIS
SUMMARY OF RESULTS AND CONCLUSIONS

- CLOSE AGREEMENT BETWEEN PRETEST/POST TEST THERMAL PREDICTIONS AND RETROREFLECTOR TEST TEMPERATURE LEVELS (MOST TEMPERATURE PREDICTIONS ARE WITHIN 5°C OF THEIR CORRESPONDING TEST LEVELS).

- APPROXIMATE 20% DEGRADATION IN OPTICAL PERFORMANCE FROM AN ISOTHERMAL CORNER DUE TO THERMAL PERTURBATION (MAXIMUM ALLOWABLE DEGRADATION IS 50%).

- THE PROPOSED THERMAL/STRUCTURAL MOUNTING SCHEME (TEST ITEM) PROVIDES THE REQUIRED RETROREFLECTOR OPTICAL RETURN LEVEL.

- HIGH DEGREE OF CONFIDENCE THAT THERMAL/OPTICAL SATELLITE FLIGHT PERFORMANCE PREDICTIONS WILL BE ACCURATE.

LAGEOS

THERMAL/OPTICAL DESIGN OBJECTIVES

- PROVIDE A THERMAL DESIGN WHICH MAINTAINS INDIVIDUAL RETROREFLECTORS IN A NEARLY ISOTHERMAL STATE TO OPTIMIZE OPTICAL PERFORMANCE.

- HIGH THERMAL RESISTANCE MOUNTING OF RETROREFLECTORS

    1. LOW IR EMITTANCE OF CAVITY, AND

    2. LOW THERMAL CONDUCTANCE BETWEEN RETROREFLECTOR TAB AND ASSOCIATED MOUNTING RINGS.

- UTILIZE THERMAL/OPTICAL COATINGS AND FINISHES ON SATELLITE EXTERIOR SURFACE THAT MINIMIZE RETROREFLECTOR-TO-CAVITY TEMPERATURE DIFFERENCES.

LAGEOS

ORBITAL ENVIRONMENT PARAMETERS

- ORBIT CHARACTERISTICS

  ORBITAL ALTITUDE = 5900 KM
  EQUATORIAL INCLINATION = 110°
  ORBITAL ECCENTRICITY $\leq$ 0.01
  SATELLITE ATTITUDE = NO PREFERRED ORIENTATION
  SATELLITE SPIN RATE = NO SPIN

- ORBITAL HEATING CONSTANTS*

  MAXIMUM DIRECT SOLAR = 1412.5 W/M^2 (WINTER SUN & MEASUREMENT ACCURACY TOLERANCE)

  MAXIMUM ALBEDO = 38.1 W/M^2 (ALBEDO REFLECTANCE = 30%)

  MAXIMUM EARTH IR = 66.5 W/M^2 ($-19^{\circ}C$ EQUIVALENT BLACK BODY TEMPERATURE).

*BASED ON INFORMATION CONTAINED IN MSFC TMX-64627 AND S&E-ASTN-PF 72-67.

LAGEOS

ORBITAL ENVIRONMENT PARAMETERS

- ORBIT CHARACTERISTICS

  ORBITAL ALTITUDE = 5900 KM
  EQUATORIAL INCLINATION = 110°
  ORBITAL ECCENTRICITY $\leq$ 0.01
  SATELLITE ATTITUDE = NO PREFERRED ORIENTATION
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  MAXIMUM DIRECT SOLAR = 1412.5 W/M^2 (WINTER SUN & MEASUREMENT ACCURACY TOLERANCE)

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  MAXIMUM EARTH IR = 66.5 W/M^2 (-19°C EQUIVALENT BLACK BODY TEMPERATURE).

*BASED ON INFORMATION CONTAINED IN MSFC TMX-64627 AND S&E-ASTN-PF 72-67.

LAGEOS

THERMO-PHYSICAL PROPERTIES

RETROREFLECTOR

THERMAL CONDUCTIVITY

TEMP (°C)	K (CAL/SEC CM°C)
-50	0.0030
20	0.0033
100	0.0035

SPECIFIC HEAT

TEMP (°C)	Cp (CAL/GM°C)
-100	0.12
-50	0.14
0	0.17
100	0.23

SPECIFIC GRAVITY = 2.20
IR EMITTANCE = 90%
VOLUMETRIC SOLAR ABSORPTANCE = 5%

SATELLITE (BARE MACHINED ALUMINUM)

SOLAR ABSORPTANCE = 37%
IR EMITTANCE = 5%

NOTE: AFTER CORRELATION WITH THERMAL/VACUUM TEST DATA THE RETROREFLECTOR VOLUMETRIC SOLAR ABSORPTANCE WAS MODIFIED TO 2.5% AND THE SATELLITE SOLAR ABSORPTANCE WAS MODIFIED TO 15%. ALL OTHER THERMO-PHYSICAL PROPERTIES REMAINED THE SAME.

LAGEOS

PRETEST RETROREFLECTOR AND MOUNT THERMAL PREDICTIONS*

ENVIRONMENTAL CONDITION	RETRO CAVITY	RETRO FACE	LOWER KEL-F RING	UPPER KEL-F RING	RETAINER RING	RETRO ΔT AXIAL	RETRO ΔT RADIAL
FULL SUN, NO IR	+30°C	2.8°C	30.1°C	51.1°C	51.3°C	1.9°C	1.3°
NO SUN, IR	+30°C	-12.1°C	29.8°C	14.9°C	14.9°C	1.4°C	0.9°C
NO SUN, NO IR	+30°C	-20.9°C	29.8°C	12.4°C	12.4°C	1.6°C	1.1°C
FULL SUN, NO IR	-30°C	-34.7°C	-29.8°C	6.9°C	7.2°C	1.0°C	0.6°C
NO SUN, IR	-30°C	-51.7°C	-30.1°C	-35.5°C	-35.5°C	0.4°C	0.3°C
NO SUN, NO IR	-30°C	-64.5°C	-30.1°C	-38.2°C	-38.2°C	0.6°C	0.5°C

NOTE: CHAMBER PRESSURE AND TEMPERATURE MAINTAINED AT LESS THAN 1×10^{-6} TORR AND -185°C, RESPECTIVELY

*BARE, MACHINED 6061-T6 ALUMINUM SATELLITE AND RETAINER RING EXTERIOR SURFACE FINISH

LAGEOS

THERMAL ANALYSIS OF RECESSED RETROREFLECTOR*

ENVIRONMENTAL CONDITION	RECESS DEPTH	CAVITY TEMP	RETRO FACE TEMP	ΔT AXIAL	ΔT RADIAL
NO SUN, NO IR	1.0 MM	+30°C	-20.9°C	1.6°C	1.1°C
	1.0 CM	+30°C	- 7.2°C	1.2°C	0.8°C
SUN, NO IR	1.0 MM	+30°C	2.8°C	1.9°C	1.3°C
	1.0 CM	+30°C	18.3°C	1.4°C	0.9°C
NO SUN, IR	1.0 MM	+30°C	-12.1°C	1.4°C	0.9
	1.0 CM	+30°C	2.1°C	0.9°C	0.6

NOTE: PRELIMINARY STUDIES CONDUCTED BY MSFC INDICATED THAT FOR 1.0 CM RETROREFLECTOR RECESSION THE SATELLITE OPTICAL RETURN COULD BE REDUCED BY 30% DUE TO OBSCURATION.

*BARE, MACHINED 6061-T6 ALUMINUM SATELLITE AND RETAINER RINGS.

LAGEOS

RETROREFLECTOR TEMPERATURE GRADIENT INPUT TO ITEK

ITEK CASE NUMBER	RETROREFLECTOR ΔT AXIAL	RETROREFLECTOR ΔT RADIAL	DESCRIPTION
2.3.b 2.4.b.2	1.9°C	1.3°C	BARE, MACHINED, 6061-T6 ALUMINUM RETAINER RING AND SATELLITE; +30°C CAVITY; FULL SUN; NO IR.
2.3.a.1	1.0°C	0.4°C	Z-93 COATING ON RETAINER RING AND SATELLITE EXTERIOR SURFACE; BARE, MACHINED ALUMINUM CAVITY AT -30°C; FULL SUN; NO IR.
2.3.a.2	3.5°C	2.0°C	ESTIMATED MAXIMUM RETROREFLECTOR TEMPERATURE GRADIENTS.
2.5.a	2.0°C	0°C	HYPOTHETICAL AXIAL TEMPERATURE GRADIENT.
2.5.b	0°C	2.0°C	HYPOTHETICAL RADIAL TEMPERATURE GRADIENT.

NOTE: ISOTHERMAL RETROREFLECTOR TEMPERATURE = 25°C (USED IN ITEK CASE NUMBERS 2.1, 2.2, AND 2.4.a.)

LAGEOS

RESULTS OF PRETEST THERMAL DESIGN PARAMETRIC STUDIES

INDEPENDENT HEAT TRANSFER PARAMETRIC STUDIES CONDUCTED AT MSFC AND BxA INDICATED THAT THE FOLLOWING THERMAL DESIGN FEATURES ARE NECESSARY TO ACHIEVE A NEARLY ISOTHERMAL RETROREFLECTOR.

1. LOW CAVITY IR EMITTANCE - BARE, MACHINED 6061-T6 ALUMINUM POSSESSES AN IR EMITTANCE OF 5%.

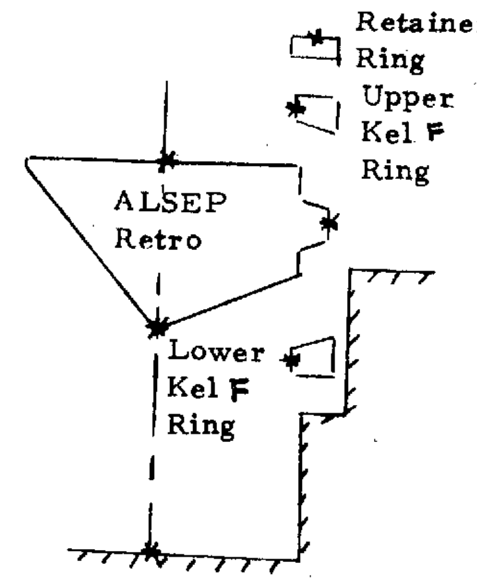
2. LOW MOUNT CONDUCTANCE - KEL-F RINGS WERE DESIGNED TO PROVIDE A 0.003 TO 0.005 INCH RETROREFLECTOR TAB/MOUNT CLEARANCE TO MINIMIZE CONDUCTION HEAT TRANSFER.

3. REFLECTIVE THERMAL CONTROL COATINGS FOR SATELLITE EXTERIOR SURFACES - LOW SOLAR ABSORPTANCE/HIGH IR EMITTANCE COATINGS REDUCE RETROREFLECTOR/CAVITY TEMPERATURE DIFFERENTIALS AND HEAT INTERCHANGE.

LAGEOS

DESCRIPTION OF THERMOCOUPLE FIXTURE

- THERMOCOUPLE FIXTURE CONTAINS TWO INSTRUMENTED ALSEP RETROREFLECTORS AND IS MOUNTED TO THE LAGEOS THERMAL/VACUUM TEST FIXTURE.
- CONDUCTIVE MOUNTING INTERFACE FOR LAGEOS/ ALSEP RETROREFLECTORS IS IDENTICAL.
- LAGEOS/ALSEP RETROREFLECTORS ARE EXPOSED TO IDENTICAL INTERNAL AND EXTERNAL RADIATION THERMAL ENVIRONMENTS.
- ADDITIONAL THERMOCOUPLE INSTRUMENTATION LOCATED ON UPPER AND LOWER KEL-F RINGS, RETAINER RING, AND RETROREFLECTOR CAVITY.
- LAGEOS RETROREFLECTOR PANEL TEMPERATURE WAS ALSO MONITORED.



THERMOCOUPLE FIXTURE

LAGEOS

COMPARISON OF THERMAL ANALYSIS/TEST DATA

TEST NUMBER	DATE/TIME	ENVIRONMENTAL CONDITION	THERMAL ANALYSIS			THERMAL TEST		
			CAVITY	RETRO FACE	RETAINER RING	CAVITY	RETRO FACE	RETAINER RING
19	8-13-74/0723	NO SUN, NO IR	-30.0°C	-64.5°C	-38.2°C	-30.0°C	-62.5°C	-36.0°C
9	8-9-74/0711	NO SUN, IR	-30.0°C	-51.7°C	-35.5°C	-30.5°C	-47.0°C	-33.5°C
8	8-9-74/1456	FULL SUN, NO IR	-30.0°C	-34.7°C	7.2°C	-29.5°C	-43.5°C	-17.0°C
3	8-10-74/0226	NO SUN, NO IR	+30.0°C	-20.9°C	12.4°C	30.5°C	-23.5°C	21.0°C
6	8-9-74/2330	NO SUN, IR	+30.0°C	-12.1°C	14.9°C	29.0°C	-13.5°C	21.5°C
4	8-9-74/2000	FULL SUN, NO IR	+30.0°C	2.8°C	51.3°C	29.5°C	-20.0°C	21.5°C

LAGEOS

POST TEST THERMAL ANALYSIS AND ANALYSIS/TEST CORRELATION (TEST ARTICLE)

TEST NUMBER	DATE/TIME	ENVIRONMENTAL CONDITION	ANALYSIS			TEST		
			CAVITY	RETRO FACE	RETAINER RING	CAVITY	RETRO FACE	RETAINER RING
5	8-12-74/1621	NO SUN, NO IR	60.0°C	1.0°C	36.5°C	61.5°C	- 1.0°C	38.0°C
4*	8-9-74/2000	FULL SUN, NO IR	30.0°C	-10.1°C	29.1°C	29.5°C	-20.0°C	21.5°C
8*	8-9-74/2330	FULL SUN, NO IR	-30.0°C	-50.8°C	-18.6°C	-29.5°C	-43.5°C	-17.0°C

*CORRELATED THERMAL/MATHEMATICAL MODEL (BASED ON THERMAL VACUUM TEST DATA).

1. RETROREFLECTOR VOLUMETRIC SOLAR ABSORPTANCE MODIFIED FROM 5.0% TO 2.5%.
2. SOLAR ABSORPTANCE OF BARE, MACHINED ALUMINUM MODIFIED FROM 37% TO 15%.
3. ALL OTHER LAGEOS THERMAL ANALYSIS ASSUMPTIONS REMAIN UNCHANGED.

RETROREFLECTOR THERMAL GRADIENT INFORMATION*
(THERMAL ANALYSIS)

ENVIRONMENTAL CONDITIONS	CAVITY TEMP	RETRO FACE	ΔT AXIAL	ΔT RADIAL
NO SUN, NO IR	-30°C	-65.4°C	0.6°C	0.5°C
NO SUN, IR	-30°C	-51.7°C	0.4°C	0.3°C
FULL SUN, NO IR**	-30°C	-50.8°C	0.8°C	0.5°C
NO SUN, NO IR	+30°C	-20.9°C	1.6°C	1.1°C
NO SUN, IR	+30°C	-12.1°C	1.4°C	0.9°C
FULL SUN, NO IR**	+30°C	-10.1°C	1.8°C	1.2°C
NO SUN, NO IR	+60°C	1.0°C	2.4°C	1.5°C

*BARE MACHINED 6061-T6 ALUMINUM RETAINER RING
**CORRELATED THERMAL MODEL

LAGEOS

SATELLITE THERMAL ANALYSIS ASSUMPTIONS*

ORBIT PARAMETERS

ALTITUDE = 5900 KM
EQUATORIAL INCLINATION = 110°
ECCENTRICITY $\leq$ 0.01
FULL SUNLIT ORBIT (NO ECLIPSE)

SATELLITE ATTITUDE

SPIN RATE = 0
SATELLITE EQUATOR PLANE PERPENDICULAR TO ECLIPTIC
SATELLITE EQUATOR AND TERMINATOR ARE COINCIDENT

SATELLITE THERMAL/OPTICAL PROPERTIES

EXTERIOR SURFACES (SATELLITE STRUCTURE AND RETAINER RINGS)
α_s/ϵ_{ir} = 0.15/0.05 (BARE MACHINED 6061-T6 ALUMINUM)

INTERIOR SURFACES
ϵ_{ir} = 0.05 (BARE MACHINED 6061-T6 ALUMINUM)

*SATELLITE THERMAL ANALYSIS INCLUDES CORRELATED PROPERTIES OF RETROREFLECTOR VOLUMETRIC SOLAR ABSORPTANCE AND SATELLITE SOLAR ABSORPTANCE.

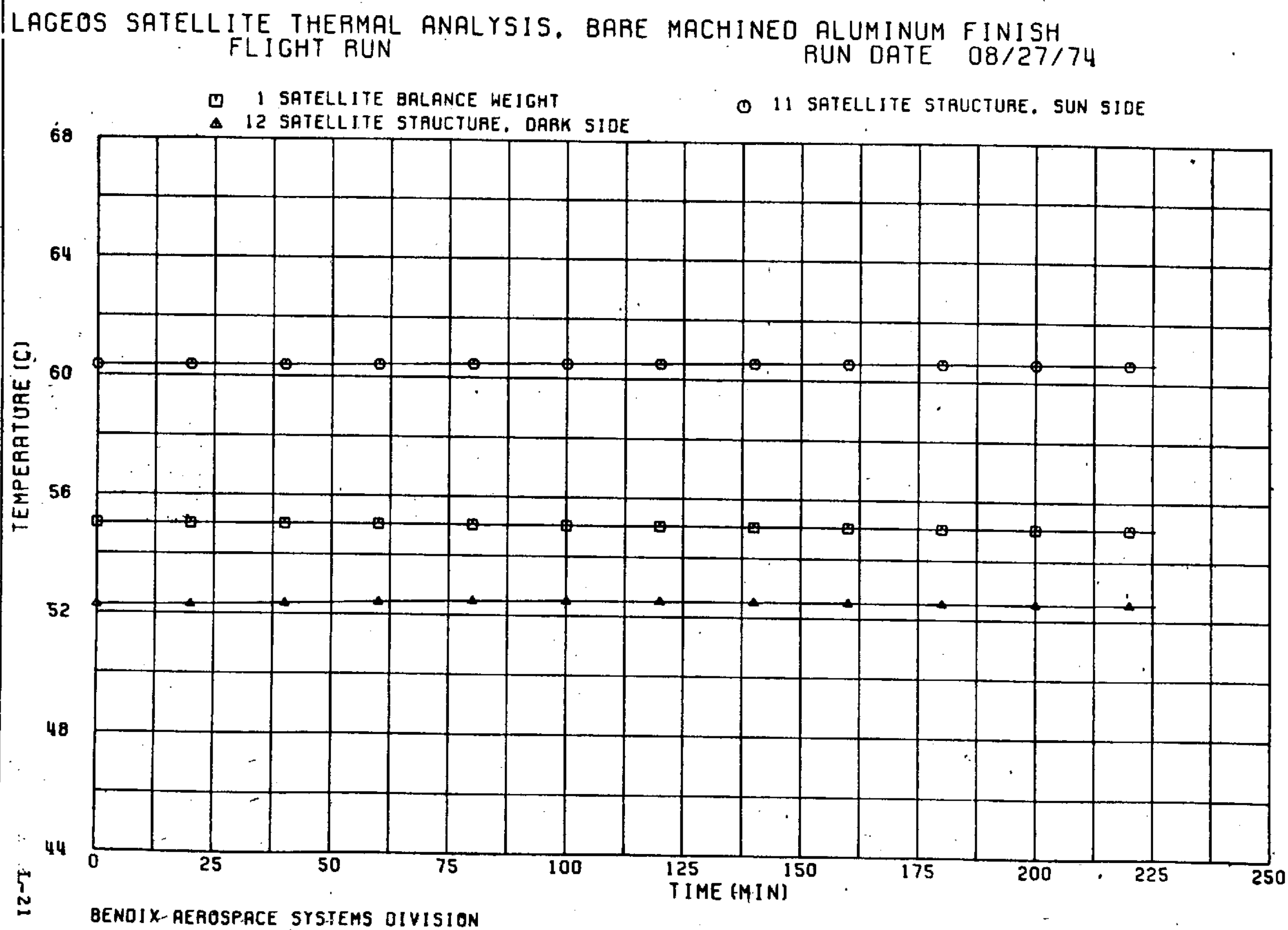
LAGEOS

DESCRIPTION OF SATELLITE THERMAL/MATH MODEL

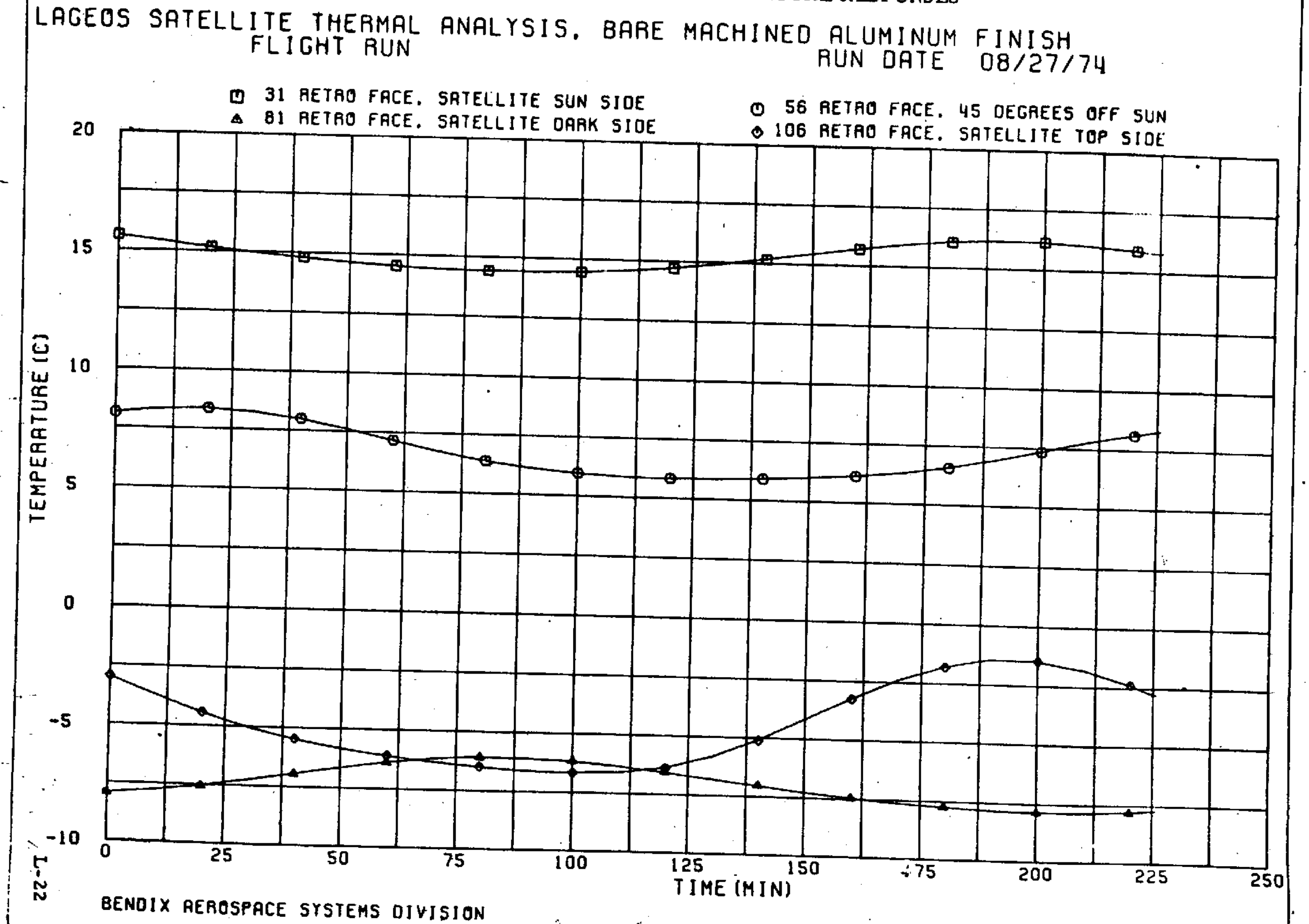
ITEM	NODE IDENTIFICATION	NUMBER OF NODES
BALANCE WEIGHT (30M20456)	1, 2	2
HALF SPHERE (30M20459)	3-12	10
INDIVIDUAL RETROREFLECTORS (50M24461)	25-42 RETRO #1, FULL SUN 50-67 RETRO #2, 45° OFF SUN 75-92 RETRO #3, 180° OFF SUN 100-117 RETRO #4, 90° OFF SUN	18 PER RETRO 72 TOTAL
INDIVIDUAL RETAINER RINGS (50M23170)	43 RETRO #1 68 RETRO #2 93 RETRO #3 118 RETRO #4	4
INDIVIDUAL KEL F RINGS, UPPER & LOWER (50M24459, P/N 1 & 2)	44-49 RETRO #1 69-74 RETRO #2 94-99 RETRO #3 119-124 RETRO #4	6 PER RETRO 24 TOTAL
COMBINED RETROS, KEL F RINGS, RETAINER RINGS	125-164	40
SPACE	201-206	6
TOTAL NODES	-	158

TOTAL NUMBER OF RADIATION AND CONDUCTION RESISTORS = 483

SATELLITE STRUCTURE STABILIZATION TEMPERATURES

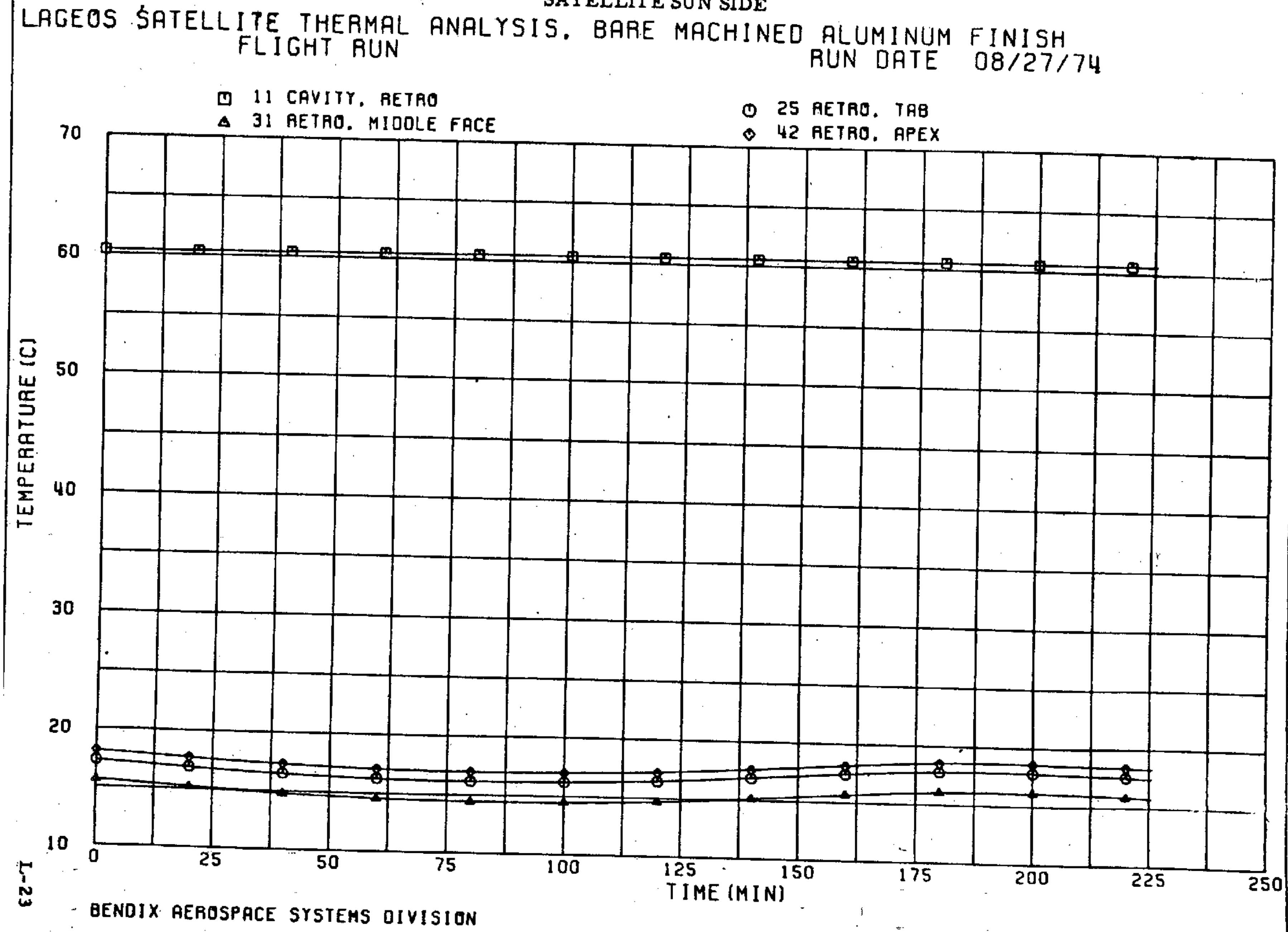


TYPICAL RETROREFLECTOR TEMPERATURE RESPONSES

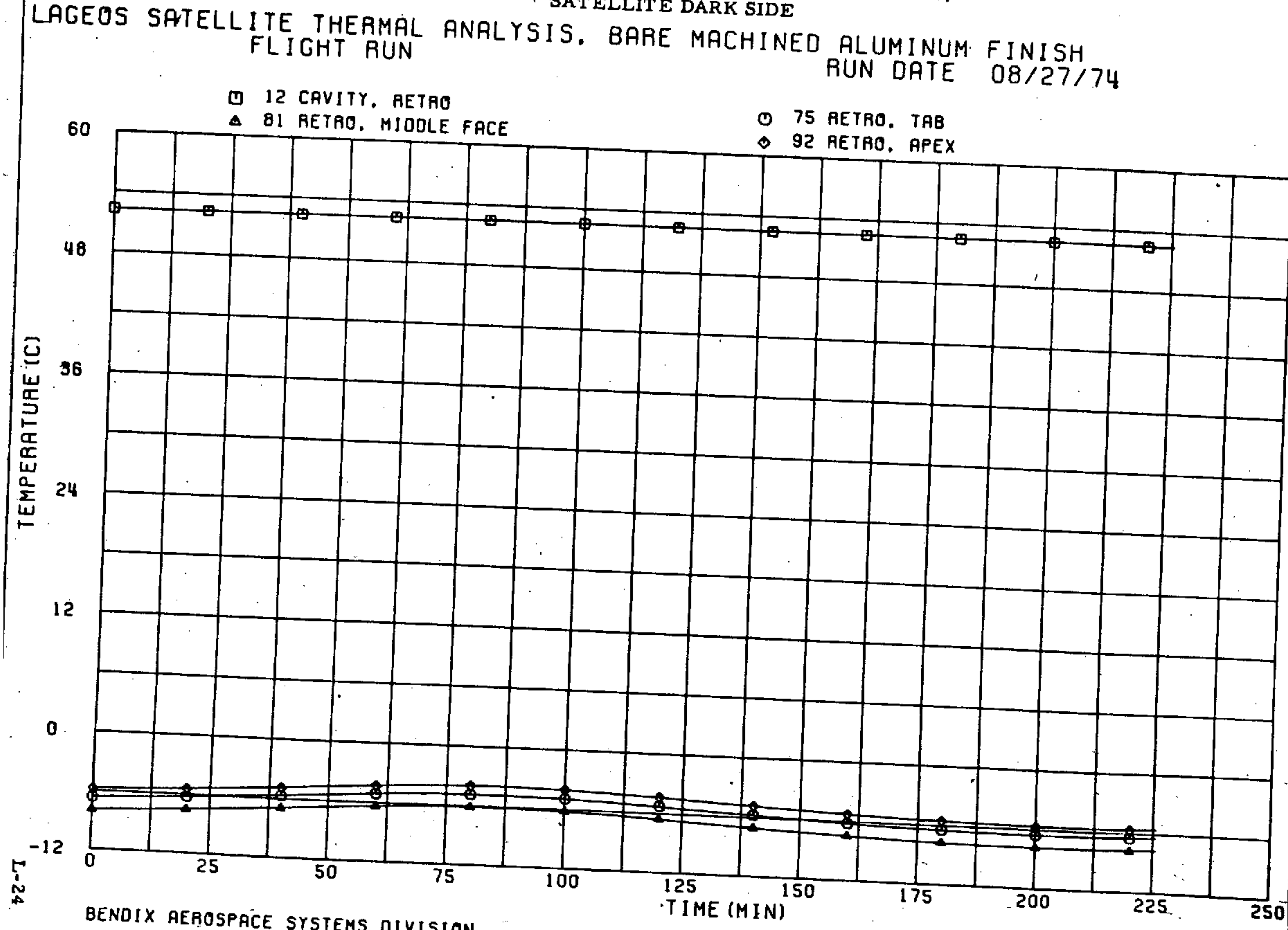


L-22

RETROREFLECTOR TEMPERATURE DISTRIBUTIONS,
SATELLITE SUN SIDE



RETROREFLECTOR TEMPERATURE DISTRIBUTIONS, SATELLITE DARK SIDE



)

LAGEOS

SUMMARY OF SATELLITE FLIGHT THERMAL ANALYSIS RESULTS*

LOCATION	RETRO #1 FULL SUN	RETRO #2 45° OFF SUN	RETRO #3 180° OFF SUN	RETRO #4 90° OFF SUN	AVERAGE
RETRO TEMPERATURE	16.0°C	8.5°C	-7.5°C	-2.5°C	3.6°C
ΔT AXIAL	2.5°C	2.2°C	2.1°C	2.3°C	2.3°C
ΔT RADIAL	1.7°C	1.5°C	1.3°C	1.2°C	1.4°C

NOTE: 1. SATELLITE CORE TEMPERATURE = 54.0°C.

2. APPROXIMATE 8°C GRADIENT ACROSS SATELLITE STRUCTURE.

*BARE MACHINED 6061-T6 ALUMINUM SATELLITE AND RETAINER RINGS.

LAGEOS

EFFECT OF RETROREFLECTOR TEMPERATURE GRADIENTS ON OPTICAL PERFORMANCE

ITEM	ISOTHERMAL OPTICAL PERFORMANCE		THERMALLY PERTURBED OPTICAL PERFORMANCE		
			THERMAL/OPTICAL ANALYSIS		THERMAL/ OPTICAL TEST
	ITEK	FFDI	BXA/ITEK THERMAL/OPTICAL	BXA SATELLITE ANALYSIS	FFDI DATA
RETRO FACE TEMPERATURE	25.0°C	25.0°C	2.8°C	3.6°C	-5.0°C[1]
RETRO ΔT AXIAL	0°C	0°C	1.9°C	2.3°C	-
RETRO ΔT RADIAL	0°C	0°C	1.3°C	1.4°C	-
OPTICAL RETURN	17.7%[2]	12.4%	16.9%[2]	-	13.5%

ANALYSIS: RETROREFLECTOR TEMPERATURE GRADIENTS DEGRADE OPTICAL PERFORMANCE BY 5% FROM ISOTHERMAL RETURN.

TEST: RETROREFLECTOR TEMPERATURE GRADIENTS IMPROVE OPTICAL PERFORMANCE BY 9% FROM ISOTHERMAL RETURN.

NOTES:
1. TEST RESULTS ADJUSTED TO CORRESPOND TO 54.0°C SATELLITE CORE TEMPERATURE.
2. CORRESPONDS TO 0° FIELD ANGLE, $\lambda/4$ WAVEFRONT, AND TOLERANCED DIHEDRAL ANGLES (1.0", 1.5", & 2.0").

LAGEOS

THERMAL DESIGN/ANALYSIS/TEST CONCLUSIONS

- THE PROPOSED LAGEOS MOUNTING ARRANGEMENT (TEST ITEM) PROVIDES ADEQUATE THERMAL CONTROL FOR THE RETROREFLECTORS.
- CLOSE CORRELATION BETWEEN THERMAL/OPTICAL ANALYSIS AND TEST RESULTS.
- HIGH DEGREE OF CONFIDENCE THAT PREVIOUSLY SPECIFIED THERMAL/OPTICAL DATA WILL BE REPRESENTATIVE OF ACTUAL LAGEOS SATELLITE ORBITAL PERFORMANCE.

LAGEOS

THERMAL DESIGN RECOMMENDATIONS

- RETROREFLECTOR CAVITY SHOULD POSSESS A LOW (LESS THAN 5%) INFRARED EMITTANCE TO ENHANCE RADIATIVE ISOLATION.
- RETROREFLECTOR MOUNTING RINGS SHOULD HAVE LOW THERMAL CONDUCTIVITY AND SHOULD PROVIDE MINIMAL OR NO CONTACT WITH THE RETROREFLECTOR TABS.
- THERMAL COATINGS/FINISHES WHICH ARE APPLIED TO THE SATELLITE EXTERIOR SHOULD BE OF LOW SOLAR ABSORPTANCE (HIGH VISIBLE REFLECTANCE) TO PERMIT TRACKING BY GROUND STATIONS.
- NO PARTICULAR LEVEL OF EXTERNAL IR EMITTANCE IS RECOMMENDED SINCE IT APPEARS TO HAVE AN INSIGNIFICANT EFFECT ON RETROREFLECTOR OPTICAL PERFORMANCE.

LAGEOS

POTENTIAL THERMAL CONTROL COATINGS/FINISHES* FOR SATELLITE EXTERIOR SURFACES

COATING/FINISH	THERMAL/OPTICAL PROPERTIES (α_S/ϵ_{IR})	ADVANTAGES	DISADVANTAGES
BARE, MACHINED 6061-T6 ALUMINUM (CLEANED & DEGREASED)	0.15-0.37/0.05	CLEAN SURFACE IS STABLE TO UV IRRADIATION; EASY TO ACHIEVE; NO MASKING OF CAVITIES NECESSARY.	SOLAR ABSORPTANCE OF UNTREATED ALUMINUM SUBJECT TO WIDE VARIATIONS; SURFACE MUST BE HANDLED WITH CARE.
6061-T6 ALUMINUM, ROUGHENED (GRIT BLASTED)	0.46/0.30	CLEANED SURFACE IS STABLE TO UV IRRADIATION; DOES NOT REQUIRE METICULOUS HANDLING TECHNIQUES.	DIFFICULT TO APPLY UNIFORMLY; CAVITIES MUST BE MASKED.
ANODIZED 6061-T6 ALUMINUM, 0.001 INCH THICK (PER MIL-A-8625, TYPE II)	0.52/0.86	INITIAL OPTICAL PROPERTIES ARE SATISFACTORY; RELATIVE EASY TO APPLY.	IN ONE YEAR α_S DEGRADES TO 0.72 IN UV ENVIRONMENT; CAVITIES MUST BE MASKED.
IIT'S Z-93 (WHITE INORGANIC COATING)	0.20/0.90	PREVIOUSLY FLOWN ON ALSEP LRRR MISSIONS; STABLE, α_S DEGRADES TO 0.30 IN ONE YEAR; SMALL ADDITIONAL DEGRADATION IN SUCCESSIVE YEARS.	DIFFICULT TO APPLY AND KEEP CLEAN, CAVITIES MUST BE MASKED.
VACUUM DEPOSITED ALUMINUM (1200 Å THICK)	0.15/0.05	NO MASKING OF CAVITIES NECESSARY; HIGH VISIBLE REFLECTANCE; STABLE.	MODERATELY DIFFICULT TO APPLY; EXTREME HANDLING PRECAUTIONS ARE NECESSARY.
VACUUM DEPOSITED GOLD	0.25/0.05	NO MASKING OF CAVITIES NECESSARY; STABLE.	MODERATELY DIFFICULT TO APPLY; EXTREME HANDLING PRECAUTIONS ARE NECESSARY.

*THERMAL COATINGS/FINISHES SELECTED ON THE BASIS OF COMPATIBILITY WITH 6061-T6 ALUMINUM, LOW SOLAR ABSORPTANCE (HIGH VISIBLE REFLECTANCE), AND STABILITY.

Bendix

Aerospace
Systems Division

LAGEOS OPTICAL ANALYSIS/TESTS

LAGEOS THERMAL/OPTICAL ANALYSIS PRESENTATION

- PURPOSE OF THERMAL/OPTICAL ANALYSIS - BENDIX
- SUMMARY OF ANALYSIS CASES/RESULTS - BENDIX
- OPTICAL ANALYSIS EFFORT - ITEK

LAGEOS

PURPOSE OF THE OPTICAL ANALYSIS

- GENERATE PREDICTED OPTICAL PERFORMANCE FOR THE LAGEOS RETROREFLECTOR UNDER ISOTHERMAL AND VARIOUS THERMAL GRADIENT CONDITIONS FOR COMPARISON WITH THERMAL/OPTICAL TEST RESULTS AND TO PROVIDE CONFIDENCE IN THE LAGEOS DESIGN.

- TO DEMONSTRATE THAT OPTICAL PERFORMANCE PREDICTIONS CAN BE GENERATED FOR THE LAGEOS RETROREFLECTORS UNDER VARIOUS ORBITAL THERMAL CONDITIONS, USING AN OPTICAL ANALYSIS RETROREFLECTOR MODEL AND A THERMAL ANALYSIS SATELLITE MODEL, TO SUPPORT FUTURE LAGEOS SATELLITE SYSTEM OPERATIONS.

LAGEOS

SUMMARY OF OPTICAL ANALYSIS CASES/RESULTS

CASE	DESCRIPTION	TEMPERATURE GRADIENT	LASER FIELD ANGLE	% RETURN IN ANNULUS (32-41 μ RAD RADII)
2.1	PERFECT; 1.5"	ISOTHERMAL	0°	18.4
2.1	PERFECT; 1.5"	ISOTHERMAL	-15°	9.6
2.2	$\lambda/4$; 1.5"	ISOTHERMAL	0°	18.0
2.2	$\lambda/4$; 1.5"	ISOTHERMAL	-15°	8.8
2.4.a	$\lambda/4$; 1.0", 1.5", 2.0"	ISOTHERMAL	0°	17.7
2.4.a	$\lambda/4$; 1.0", 1.5", 2.0"	ISOTHERMAL	-15°	8.6
2.3.a.1	$\lambda/4$; 1.5"	$\Delta Ta = 1.0°C$, $\Delta Tr = 0.4°C$	0°	18.0
2.3.a.2	$\lambda/4$; 1.5"	$\Delta Ta = 3.5°C$, $\Delta Tr = 2.0°C$	0°	17.1
2.3.b	$\lambda/4$; 1.5"	$\Delta Ta = 1.9°C$, $\Delta Tr = 1.3°C$	0°	17.2
2.3.b	$\lambda/4$; 1.5"	$\Delta Ta = 1.9°C$, $\Delta Tr = 1.3°C$	-15°	8.3
2.4.b.2	$\lambda/4$; 1.0", 1.5", 2.0"	$\Delta Ta = 1.9°C$, $\Delta Tr = 1.3°C$	0°	16.9
2.4.b.2	$\lambda/4$; 1.0", 1.5", 2.0"	$\Delta Ta = 1.9°C$, $\Delta Tr = 1.3°C$	-15°	8.1
2.5.a	$\lambda/4$; 1.5"	$\Delta Ta = 2.0°C$, $\Delta Tr = 0°C$	0°	15.9
2.5.b	$\lambda/4$; 1.5"	$\Delta Ta = 0°C$, $\Delta Tr = 2.0°C$	0°	4.2

Itek

THERMO-OPTICAL ANALYSIS

LAGEOS

PREPARED UNDER

CONTRACT TO

BENDIX AEROSPACE SYSTEMS DIVISION

4 SEPTEMBER 1974

TOPICS

- PURPOSE/OBJECTIVES
- SUMMARY OF RESULTS
- ASSUMPTIONS/INPUTS
- TECHNIQUES/MODEL
- OUTPUT
- CONCLUSIONS/FUTURE EFFORT

PURPOSE/OBJECTIVES

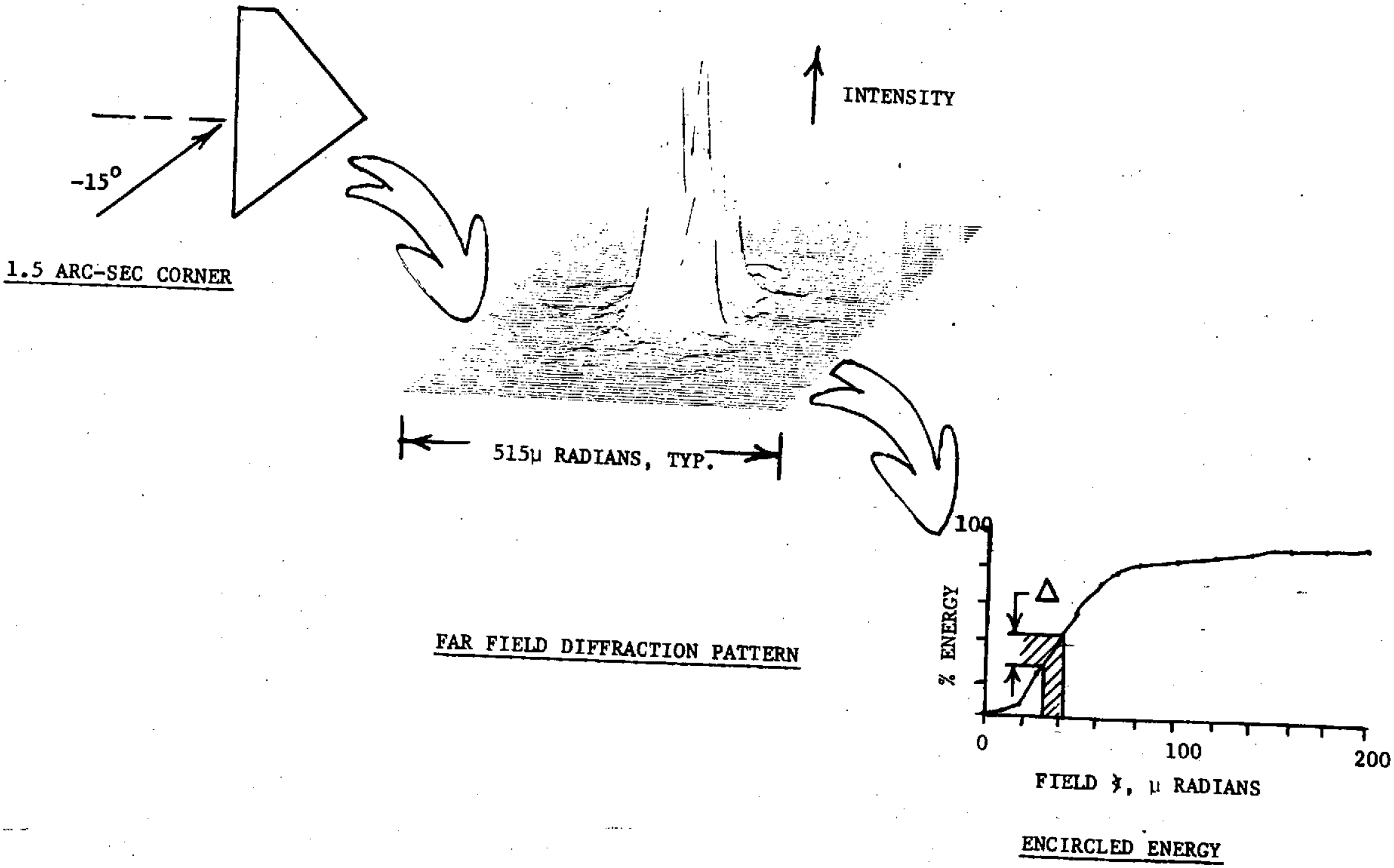
ANALYTICALLY PREDICT LAGEOS OPTICAL PERFORMANCE/SENSITIVITY

- MODEL INDIVIDUAL RETROREFLECTOR
  - MATERIAL
  - MANUFACTURING
    - SURFACE QUALITY
    - ANGULAR ANOMALIES
  - ENVIRONMENTAL LOADING

PURPOSE/OBJECTIVES CONTINUED

- FAR FIELD CHARACTERISTICS
  - FIELD ANGLE
  - POLARIZATION EFFECTS
  - ENCIRCLED ENERGY
  - FAR FIELD PATTERN

FAR-FIELD CHARACTERISTICS



SUMMARY - NOMINAL CUBE CORNERS

% ENCIRCLED ENERGY, 32 TO 42μ RADIAN REGION, TYP.

(ASSUMES 100% INPUT @ 0^{o})

	0^{o}	-15^{o}
● 1.5 ARC-SEC	21.6	10.8
● 2.1 ARC-SEC	14.9	7.3

SUMMARY OF SENSITIVITY RESULTS - MANUFACTURING

(CHANGES IN ENCIRCLED ENERGY SHOWN ARE ACTUALS, NOT %'S OF %'S)

- SURFACE QUALITY
  - UP TO 1.6% CHANGES
  - ~λ/4 PK-PK SMOOTH WFE/SECTOR
- ANGULAR DIFFERENTIALS
  - UP TO 0.4% CHANGES
  - CORNER WITH ± 0.5 ARC-SEC ANGLES
- CONSTANT ∡ ERROR
  - UP TO 8.1% CHANGES
  - 2.1 vs 1.5 ARC-SEC CORNERS

SUMMARY OF SENSITIVITY RESULTS - 3D TEMPERATURE MAPS

(FACE COOL, EDGE WARM)

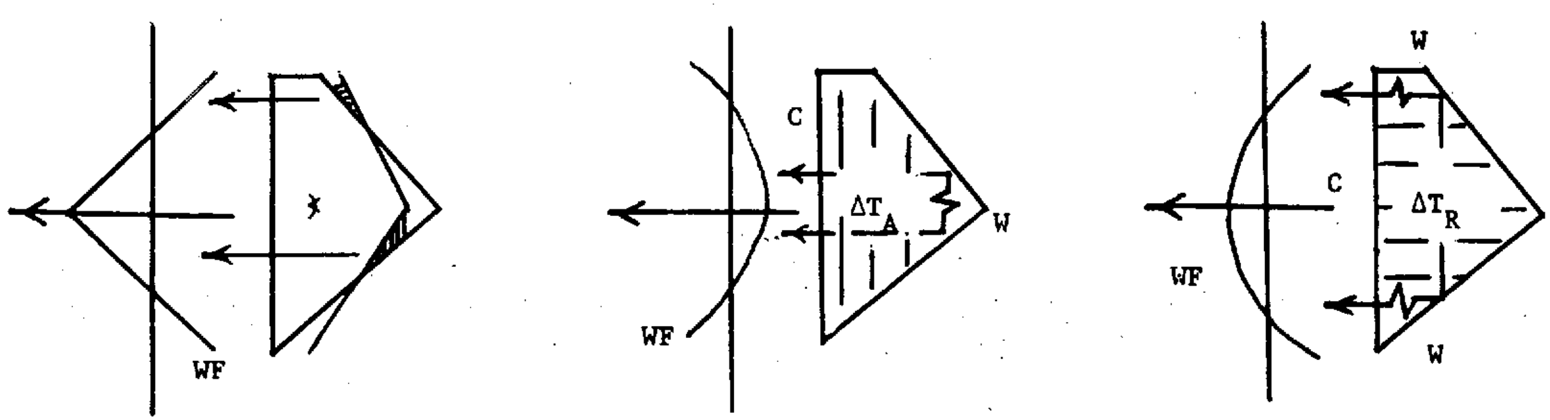
- +30°C CAVITY, W/SUN, W/O IR
  - UP TO 1.1% CHANGES
  - 1.9°C ΔT_A, 1.3°C ΔT_R
- -30°C CAVITY, W/SUN, W/O IR
  - UP TO 1.1% CHANGES
  - 1.0°C ΔT_A, 0.4°C ΔT_R
- ESTIMATED MAXIMUM
  - UP TO 1.0% CHANGES
  - 3.5°C ΔT_A, 2.0°C ΔT_R

SUMMARY OF SENSITIVITY RESULTS - UNIT LOADS

$$dw = \int_{\substack{\text{NOMINAL} \\ \text{RAY PATH}}} dn(S)\ ds$$

- 1.5°C AXIAL GRADIENT
  - 1ST REMOVES χ ERROR, THEN ADDS
  - 21.2 $\rightarrow \sim$10% (ENERGY TO CORE) $\rightarrow$ 18.0%

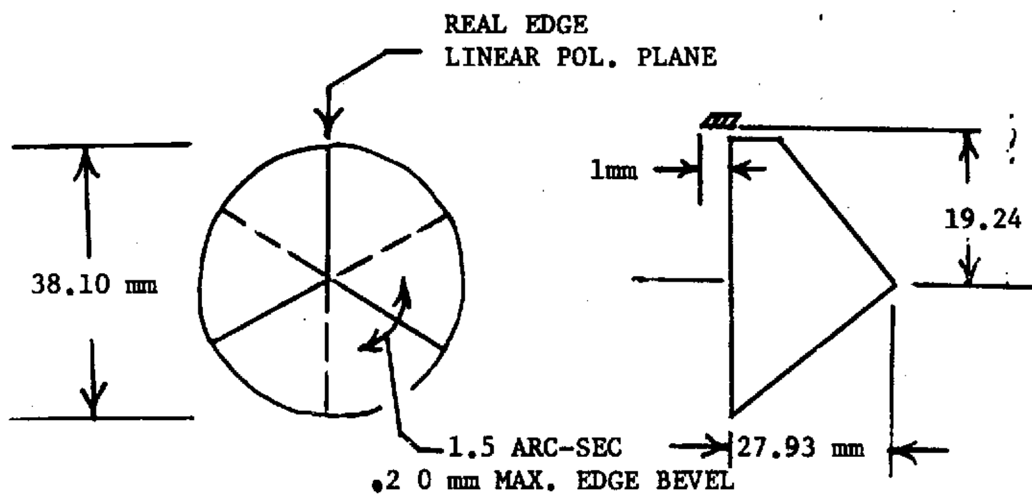
- 2.0°C RADIAL GRADIENT
  - UP TO 16.1% LOSSES



ASSUMPTIONS/INPUTS

- **MATERIAL**
  - T-19 SUPRASIL 1 (SPECIAL)
  - AMERSIL DATA - $N(\lambda)$, $\partial n/\partial T$ $(\lambda, T, P) \rightarrow 7$ to $8.5 \times 10^{-6}/^{\circ}C$
  - HOMOSIL, CONSERVATIVE

- **GEOMETRY**

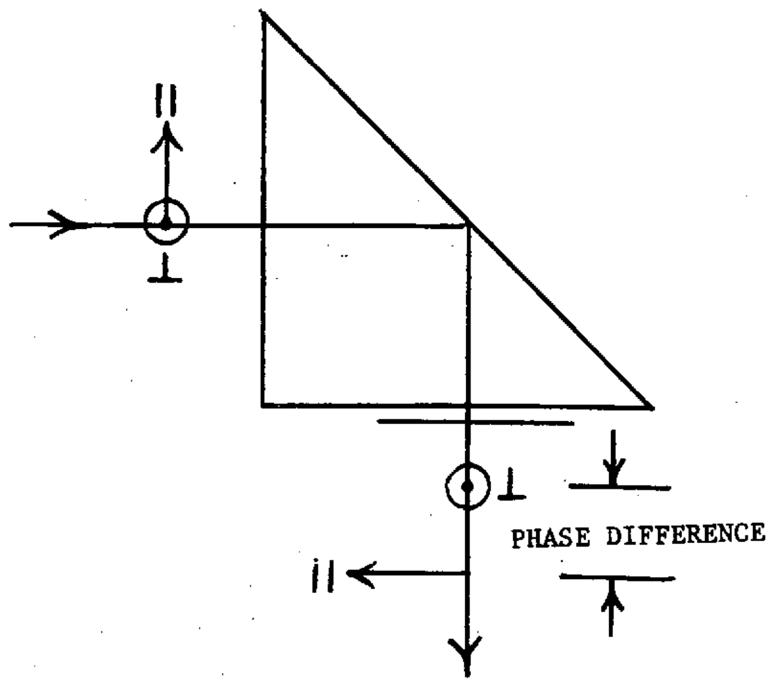


- **LASER**
  - 6328Å, FLAT WF, CENTERED
  - 20% GAUSSIAN VARIATION OVER 50 mm DIAMETER

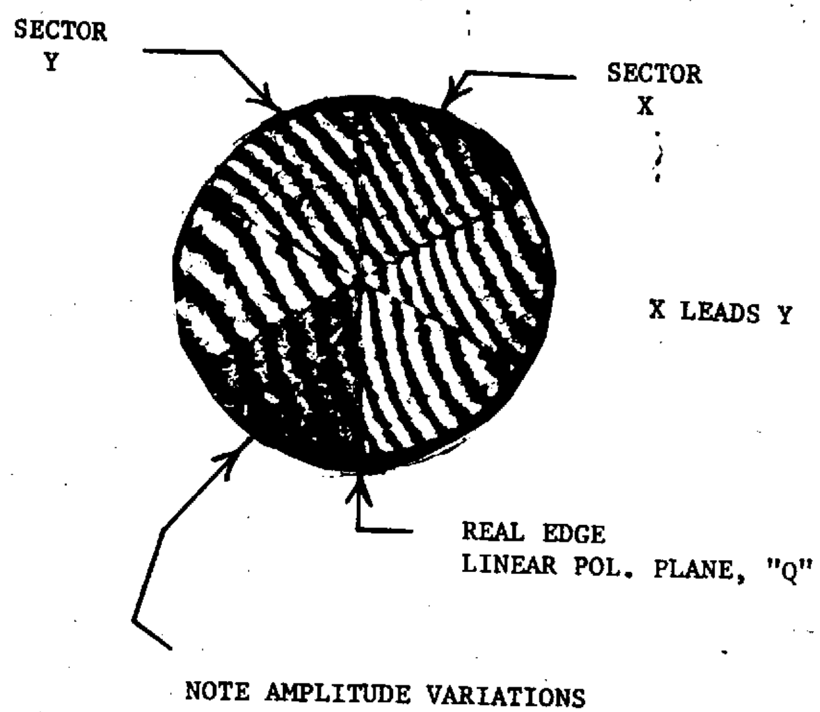
TOTAL INTERNAL REFLECTION

LIGHT REFLECTS AND POLARIZATION STATE IS CHANGED

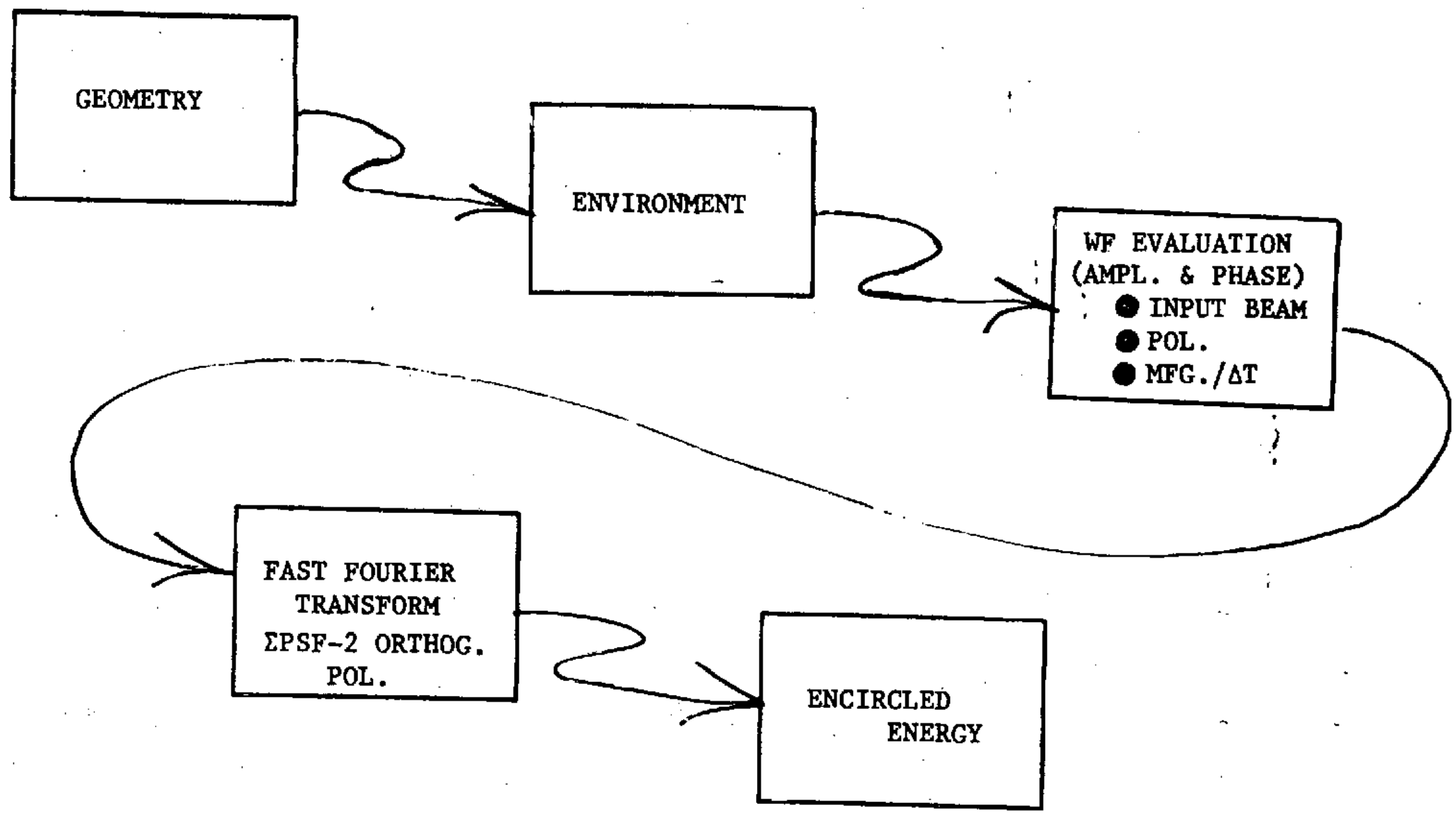
- 2-D, CARTOON



- 3-D, INTERFEROGRAM



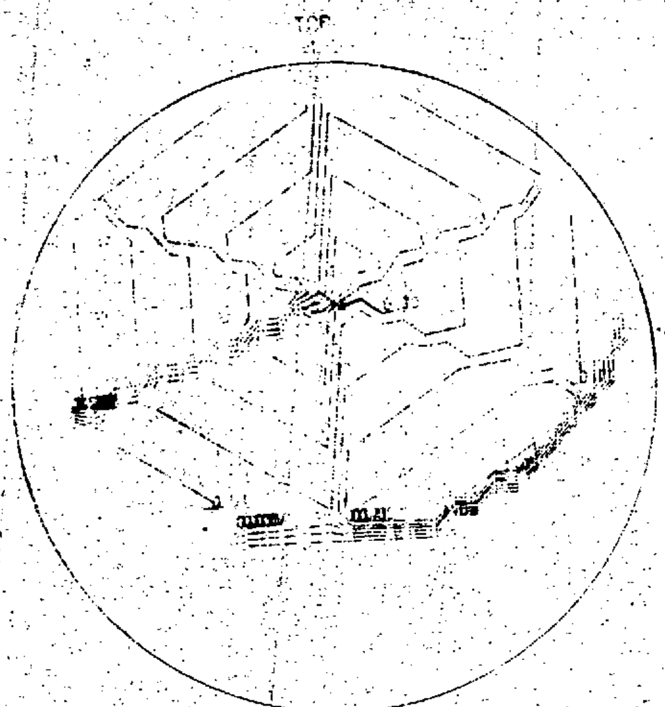
TECHNIQUES/MODEL



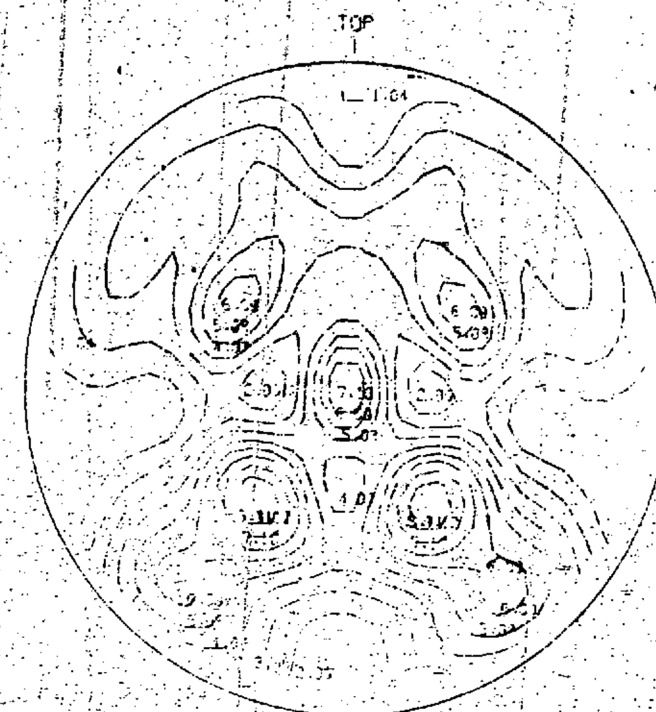
ACCURACY ~ 1% IN ENCIRCLED ENERGY

OTHER TYPES OF OUTPUT

"P/Q" AMPLITUDES & PHASES
(NOMINAL CUBE, -15°)



"P" WAVEFRONT



PSF–CENTRAL 129μ RADIANS

OUTPUT CONTINUED

TABLE 24

Task 2.1 - Nominal Cube -15° Off Axis

PRINTED MAP OF POINT SPREAD FUNCTION

(ONE SPACE REPRESENTS 8.04 MICRONS)
NORMALIZED SO LARGEST VALUE = 0.0215 = 100
TOTAL ENERGY = 0.19704000+01
MAP REPRESENTS 0.17420410+01 OR 93.1373 PERCENT OF TOTAL ENERGY

0	0	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
0	0	0	0	1	1	0	0	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	1	1	0	0	1	1	0	0	0	0
0	0	0	0	0	1	0	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	0	0	1	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	2	1	1	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	1	1	0	1	2	1	1	0	0	2	2	2	2	2	0	0	1	1	2	1	0	1	1	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	1	2	2	2	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
1	1	1	0	1	1	1	1	1	1	1	2	2	1	1	2	2	1	2	2	1	1	2	2	1	1	1	1	1	1	1	0	1	1	1
0	0	0	0	0	0	1	1	1	1	2	2	1	1	4	5	1	2	3	5	4	1	1	2	2	1	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	2	3	6	9	7	4	4	4	7	9	6	3	2	1	1	1	1	1	0	0	0	0	0	0
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1	2	2	1	2	2	3	3	4	7	13	23	36	35	38	47	45	41	45	48	38	35	36	22	12	7	4	3	3	2	2	1	2	2	1
1	1	1	0	1	2	3	2	1	6	14	29	34	30	47	56	42	37	42	56	47	30	34	28	14	6	1	2	3	2	1	0	1	1	1
1	1	1	0	1	2	3	2	1	5	15	29	30	34	66	58	32	33	32	57	65	34	30	29	15	5	1	2	3	2	1	0	1	1	1
0	1	1	0	1	2	3	2	1	5	13	23	22	30	55	34	33	62	33	34	55	30	21	23	13	5	1	2	3	2	1	0	0	1	0
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TABLE 5

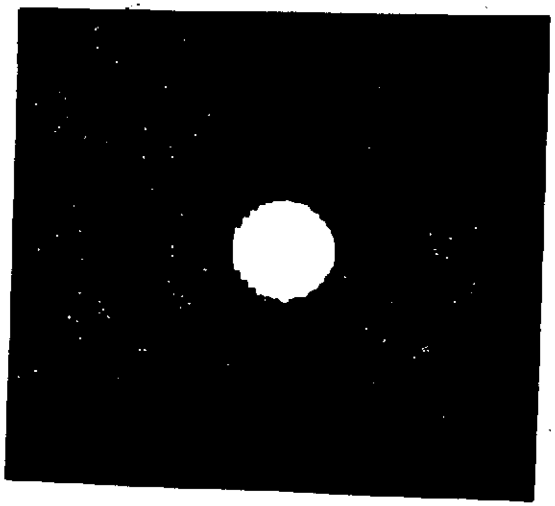
Task 2.1 - Nominal Cube -15° Off Axis

E N C I R C L E D   E N E R G Y

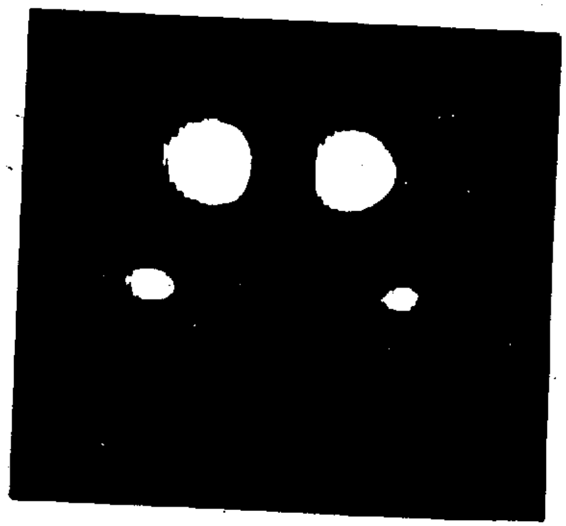
CIRCLE RADIUS (MICRONS)	PERCENT ENERGY WITHIN CIRCLE CENTERED AT INDICATED COORDINATES								
	CENTER (MICRONS):								
	X= -10.13	10.13	0.0	-10.13	0.0	10.13	0.0	-10.13	10.13
	Y= -10.13	-10.13	-10.13	0.0	0.0	0.0	10.13	10.13	10.13
2.00	0.0	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.0
4.00	0.4	0.4	0.3	0.2	0.2	0.2	0.3	0.5	0.5
6.00	0.4	0.4	0.9	0.5	1.8	0.5	1.0	0.5	0.5
8.00	1.2	1.2	1.7	1.2	1.8	1.2	1.8	1.6	1.6
10.00	1.7	1.7	2.1	1.6	3.4	1.6	2.4	2.2	2.2
12.00	3.9	3.9	3.4	3.0	3.9	3.0	3.8	4.6	4.6
14.00	3.9	3.9	4.5	4.6	4.9	4.6	5.4	4.6	4.6
16.00	6.6	6.5	5.8	6.1	5.7	6.0	7.0	7.7	7.7
18.00	7.6	7.6	7.2	7.8	8.0	7.8	8.8	9.0	9.0
20.00	9.9	9.9	9.4	9.9	8.0	9.9	11.5	11.5	11.6
22.00	11.0	11.0	11.5	12.3	11.4	12.3	14.0	12.9	12.9
24.00	13.7	13.7	13.2	13.6	13.7	13.5	15.9	16.0	16.0
26.00	15.0	15.0	16.0	16.5	17.9	16.5	18.9	17.6	17.6
28.00	18.1	18.0	19.2	19.3	19.3	19.3	22.6	20.8	20.8
30.00	20.2	20.2	21.9	22.3	24.1	22.3	25.0	23.6	23.6
32.00	24.6	24.6	24.5	24.7	27.0	24.7	27.7	27.7	27.7
34.00	25.4	25.4	27.7	28.7	30.2	28.7	30.9	28.7	28.7
36.00	30.4	30.4	30.9	31.8	34.2	31.8	34.1	33.2	33.1
38.00	32.8	32.8	34.2	35.4	37.8	35.4	34.7	35.7	35.7
40.00	36.9	36.9	37.6	38.9	39.9	38.9	40.3	39.4	39.4
42.00	39.1	39.1	41.5	43.1	43.6	43.0	43.8	41.5	41.5
44.00	43.5	43.5	44.1	45.0	46.4	45.0	46.3	45.6	45.6
46.00	46.3	46.3	47.8	49.3	50.3	49.3	50.0	48.6	48.6
48.00	49.7	49.7	51.4	52.4	52.0	52.4	53.9	51.9	51.8
50.00	52.7	52.7	53.8	55.0	56.2	55.0	56.2	55.1	55.1
52.00	55.7	55.7	56.8	57.8	59.3	57.8	59.4	58.3	58.3
54.00	57.6	57.6	59.6	60.9	62.7	60.8	62.1	60.1	60.1
56.00	60.8	60.8	62.8	64.0	65.7	63.9	65.4	63.2	63.2
58.00	63.3	63.3	64.9	66.0	68.9	66.0	67.2	65.7	65.7
60.00	65.6	65.6	67.6	68.9	71.3	68.9	69.9	67.9	67.9
62.00	67.6	67.6	69.9	71.3	73.4	71.3	71.9	69.7	69.7
64.00	70.7	70.7	71.7	73.0	75.2	73.0	73.5	72.1	72.1
66.00	72.6	72.6	74.1	75.3	77.0	75.3	75.5	73.8	73.8
68.00	74.6	74.7	76.0	76.7	77.7	76.7	76.8	75.5	75.5
70.00	76.2	76.2	77.6	78.1	79.1	78.1	78.1	76.8	76.8
72.00	78.0	78.0	78.9	79.1	80.2	79.1	79.1	78.2	78.2
74.00	79.9	78.9	80.2	80.3	81.1	80.3	80.1	79.0	79.0
76.00	80.4	80.4	81.3	81.2	81.8	81.2	81.0	80.2	80.2
78.00	81.3	81.3	81.8	81.9	82.6	81.9	81.5	81.0	81.0
80.00	82.2	82.2	82.7	82.7	83.2	82.7	82.3	81.8	81.8

ITEK LASER SCANNER RECORDER PHOTOGRAPHS

(PERFECT BK7 CORNER)



"Q" - 61 % OF TOTAL ENERGY



"P" 39 % OF TOTAL ENERGY

CONCLUSIONS

- ALL ENCIRCLED ENERGY DATA AVAILABLE FOR TEST CORRELATION.
- RETROREFLECTOR RELATIVELY INSENSITIVE - $\lambda/4$, ± 0.5 ARC-SEC.
- SENSITIVITY TO CONSTANT λ ERROR - $\leq$ 6.8% CHANGES/0.5 ARC-SEC.
- 3-D TEMPERATURE PROFILES EFFECT 32 - 42μRAD. $\sim$ 1%.
- AXIAL GRADIENTS COMPENSATE WEDGE/RADIAL GRADIENTS.
- INDEPENDENT GRADIENT TYPES HAVE FAIRLY HIGH SENSITIVITY.

RECOMMENDATIONS-ADDITIONAL EFFORT

(DEPENDENT UPON CUSTOMER/INVESTIGATOR NEEDS)

- TEST CORRELATION
  - SPECIFIC CORNER ANGLES/GEOMETRY
  - TEST EQUIPMENT EFFECTS
  - INTERFEROMETRIC/PHOTOMETRIC INPUT
  - FIELD ANGLE/APODIZATION REFINEMENT
  - INCIDENT WF QUALITY
  - FAR FIELD INTENSITY CROSS CHECKS
- ALTERNATE λ's, TREATMENT OF ARRAYS/POL. VARIATIONS
- "TRANSFER FUNCTION" SUPPORT

<u>1.5 ARC SEC CORNER</u>

ENCIRCLED ENERGY IN THE
32-42 MICRORADIAN RANGE

CASE	% ENERGY 32-42μ RAD ON AXIS	FULL
NOMINAL CUBE	21.6	10.8
NOMINAL CUBE +λ/4	21.2	9.8
NOMINAL CUBE +λ/4 +30°C CAVITY	20.4	9.4
NOMINAL CUBE +λ/4 +(-)30°C CAVITY	21.1	
NOMINAL CUBE +λ/4 + EST. MAX.	20.2	
OFF NOMINAL CUBE +λ/4	20.8	9.8
OFF NOMINAL CUBE +λ/4 + 30°C CAVITY	20.0	9.2
NOMINAL CUBE +λ/4 + AXIAL GRAD.	18.0	
NOMINAL CUBE +λ/4 + RADIAL GRAD.	5.1	

2.1 ARC-SEC CORNER
ENCIRCLED ENERGY IN THE
32-42 MICRORADIAN RANGE

CASE	% ENERGY 32-42μ RAD ON AXIS	FULL
NOMINAL CUBE	14.9	7.3
NOMINAL CUBE +λ/4	13.3	6.9
NOMINAL CUBE +λ/4 + 30°C CAVITY	12.3	6.2
NOMINAL CUBE +λ/4 + (-)30°C CAVITY	14.4	
NOMINAL CUBE +λ/4 + EST. MAX.	13.8	
OFF NOMINAL CUBE +λ/4	13.6	6.9
OFF NOMINAL CUBE +λ/4 +30°C CAVITY	12.5	6.2
NOMINAL CUBE +λ/4 + AXIAL GRAD.	19.8	
NOMINAL CUBE +λ/4 + RADIAL GRAD.	1.2	

LAGEOS

THERMAL/OPTICAL TESTS

- PURPOSE OF THERMAL/OPTICAL TESTS
- SUMMARY OF TEST RESULTS
- SUMMARY OF TEST CONDITIONS
- DESCRIPTION - TEST SET-UP
- TEST ARTICLE DESIGN
- FAR-FIELD DIFFRACTION INSTRUMENT
- TEST FIXTURES
- DETAIL TEST RESULTS
- CONCLUSIONS & RECOMMENDATIONS

PURPOSE OF THERMAL/OPTICAL TESTS

EXPERIMENTALLY DETERMINE THE THERMAL/OPTICAL PERFORMANCE OF THE LAGEOS SATELLITE RETROREFLECTOR/ MOUNT DESIGN:

- UNDER ORBITAL WORST-CASE THERMAL/ VACUUM CONDITIONS
- AFTER EXPOSURE TO SATELLITE VIBRATION QUALIFICATION LEVELS

LAGEOS

THERMAL/OPTICAL TEST RESULTS SUMMARY

- MAXIMUM DEGRADATION DUE TO W/C THERMAL CONDITIONS IS 35% (FOR RETROREFLECTOR E AT $\alpha = 0$ AND NO SUN - NO IR AT +30C CAVITY CORE TEMPERATURE)

- NO SIGNIFICANT DEGRADATION DUE TO VIBRATION EXPOSURE

- BASIC RELATIVE ANNULAR-TO-FULL FIELD RETURN, AT ISOTHERMAL-AMBIENT, VARIES FROM 6-12%, BETWEEN DIFFERENT RETROREFLECTORS AT DIFFERENT ORIENTATIONS (RELATIVE TO LASER LINEAR POLARIZATION ORIENTATION), AND FOR NORMAL LASER INCIDENT ANGLE.

LAGEOS

SUMMARY OF THERMAL/OPTICAL TEST CONDITIONS

RETROREFLECTOR ORIENTATION	TEST ARTICLE TEMP.	TEST DESCRIPTION	TEST NO.	POST VIB	NO. OF LASER INCIDENT ANGLES*
$\theta_A = 0$	AMBIENT	ISOTHERMAL-AMBIENT	1		8
$\theta_B = 90$			15		8
$\theta_C = 80$			16		8
			24	X	15
		ISOTHERMAL-VACUUM	2		15
			17		15
			18		15
	-30C THERMAL/VACUUM	NO SUN-NO IR	7		15
		NO SUN-1 EARTH IR	9		8
		1 SUN-NO IR	8		8
	+30C THERMAL/VACUUM	NO SUN-NO IR	3		15
		NO SUN-1 EARTH IR	6		8
		1 SUN-NO IR	4		8
	+60C THERMAL/VACUUM	NO SUN-NO IR	5		15 (8)

LAGEOS

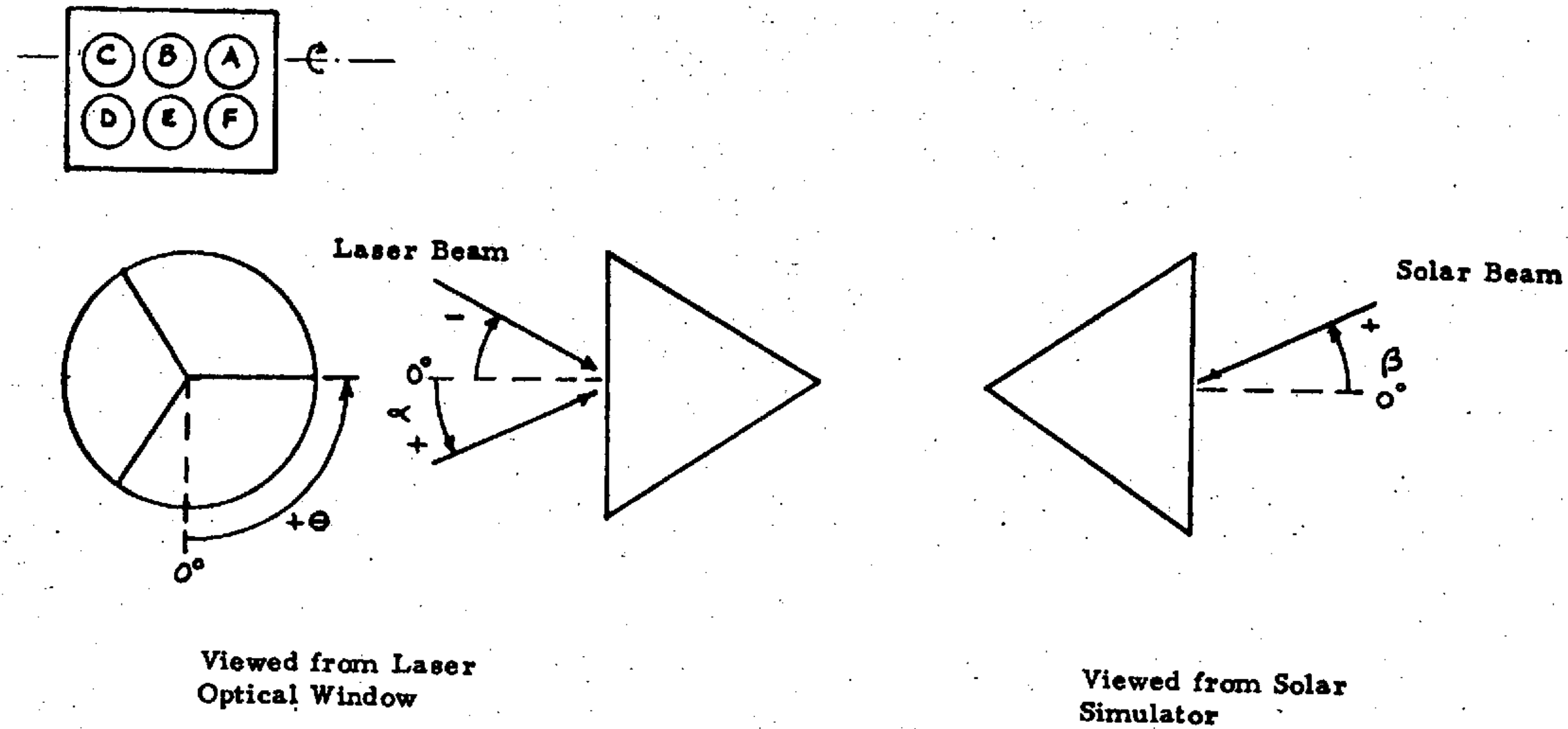
SUMMARY OF THERMAL/OPTICAL TEST CONDITIONS

RETROREFLECTOR ORIENTATION	TEST ARTICLE TEMP.	TEST DESCRIPTION	TEST NO.	POST VIB	NO. OF LASER INCIDENT ANGLES*
$\theta_D = 60$, $\theta_E = 40$, $\theta_F = 20$	AMBIENT	ISOTHERMAL-AMBIENT	10		8
		ISOTHERMAL-VACUUM	11		15 (8)
	-30C THERMAL/VACUUM	NO SUN-NO IR	19		15
	+30C THERMAL/VACUUM	NO SUN-NO IR	12		15
$\theta_D = 60$, $\theta_E = 100$, $\theta_F = 20$	AMBIENT	ISOTHERMAL-AMBIENT	20, 20A	X	15
			23	X	15
		ISOTHERMAL-VACUUM	13	X	15 (8)
	-30C THERMAL/VACUUM	NO SUN-NO IR	21	X	15
	+30C THERMAL/VACUUM	NO SUN-NO IR	14	X	15 (11)
	+60C THERMAL/VACUUM	NO SUN-NO IR	22	X	15

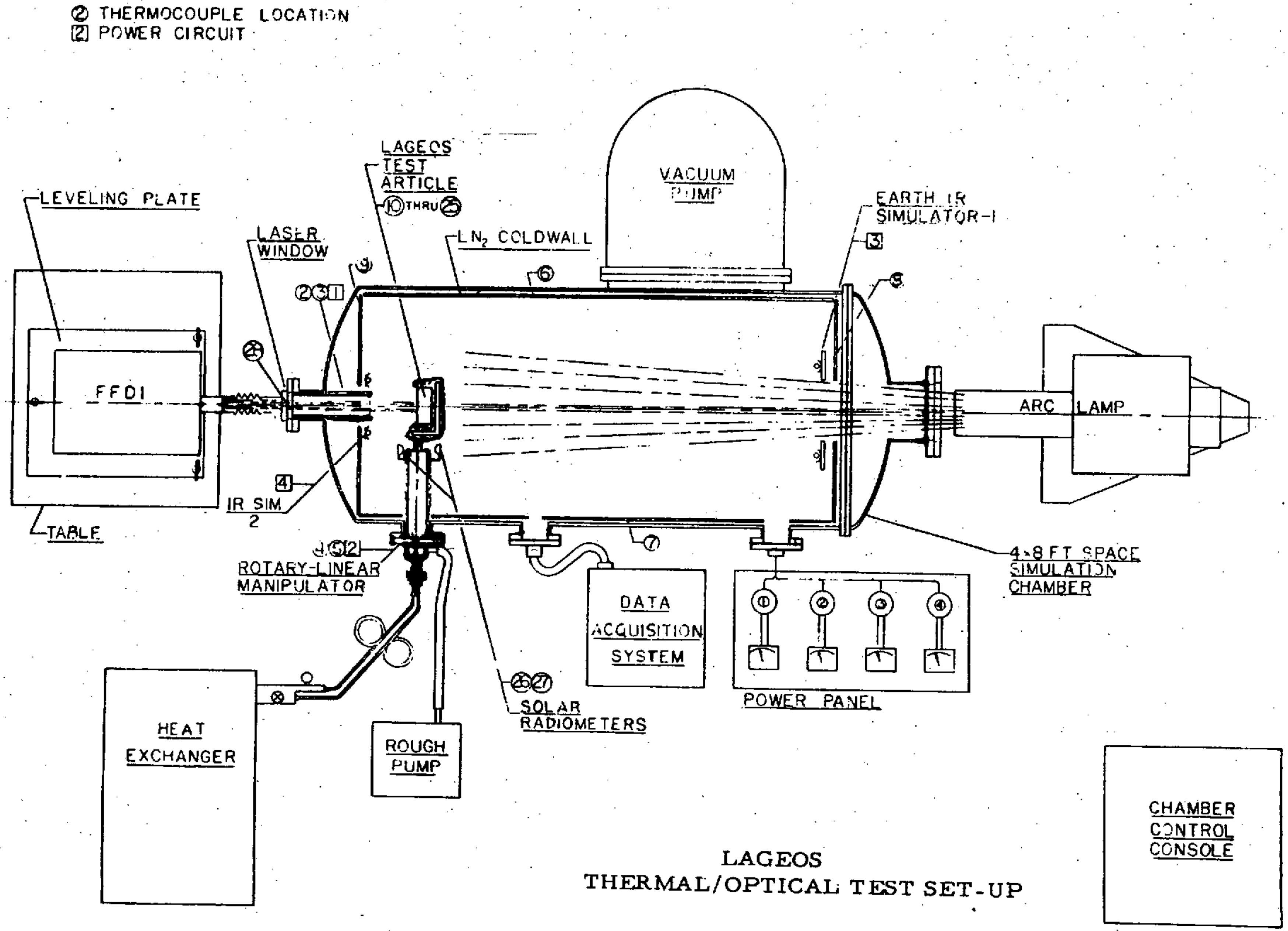
* NO. OF LASER ANGLES: 8 (A, D: α = +30, +15, -30)
B, E: α = +15, 0
C, F: α = 0

15 (A, B, C α = +30, +15, 0, -15, -30)
D, E, F

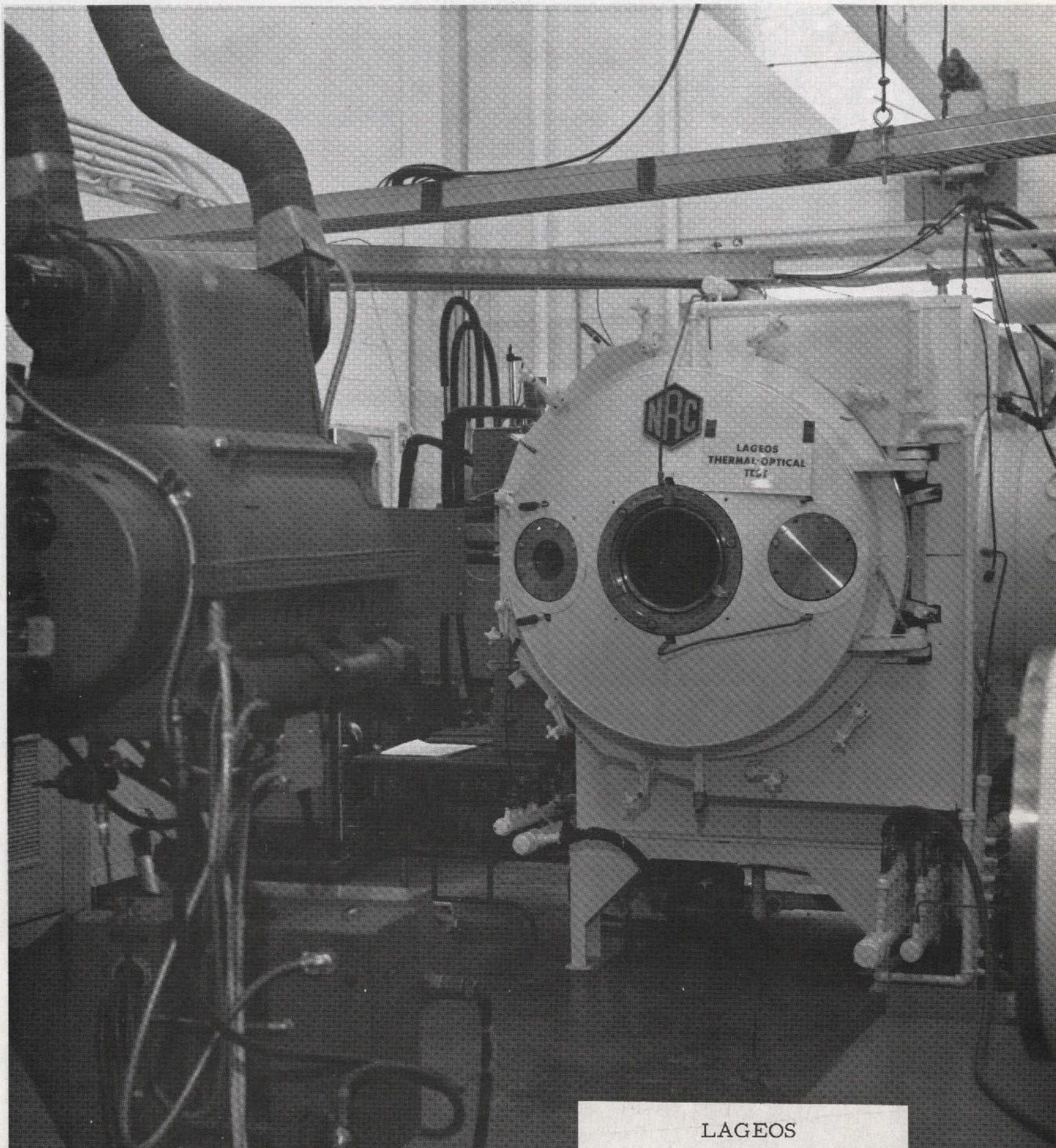
NOTE:
( ) ORIGINAL PLAN
TEST NO. > 14 ARE ADDED ABOVE ORIGINAL PLAN



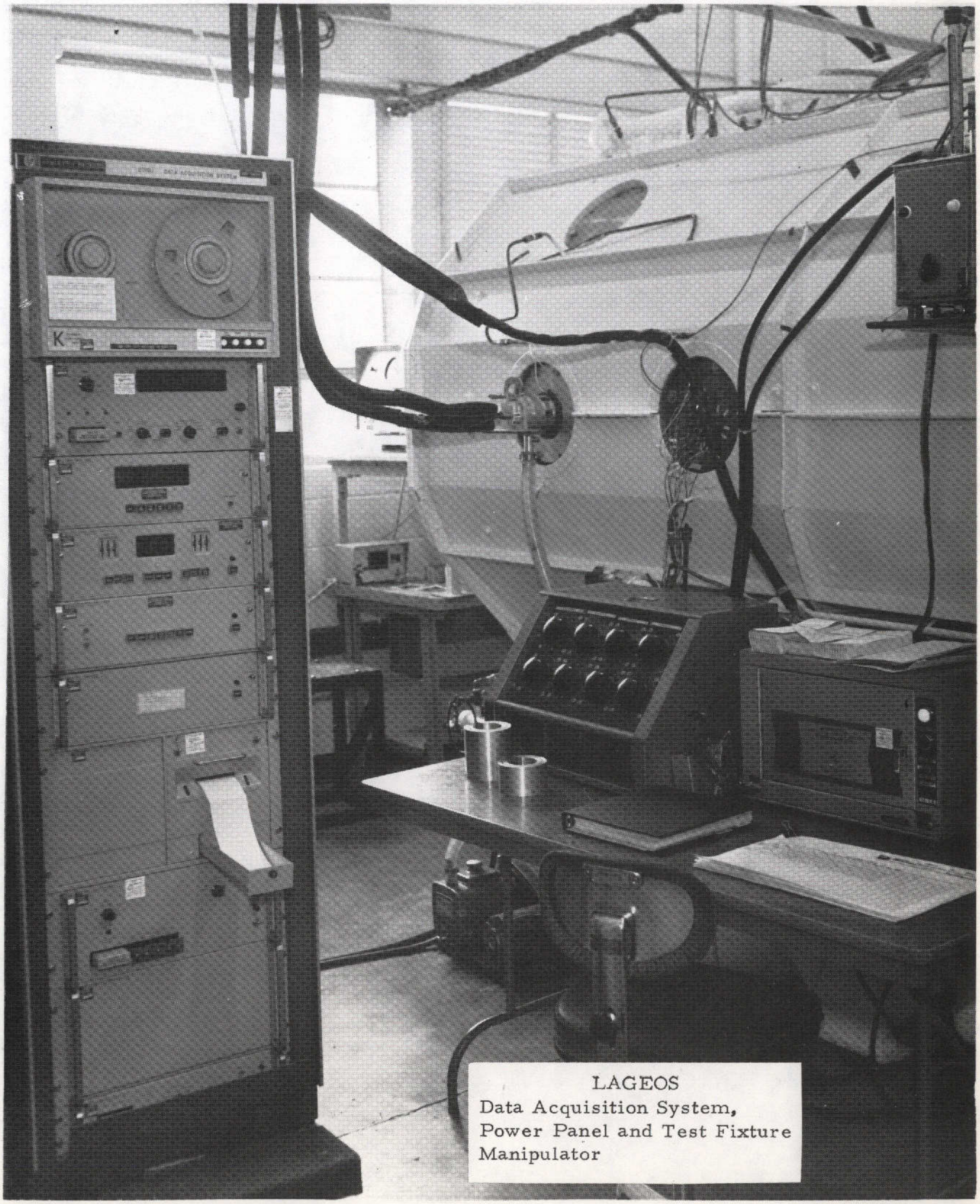
SOLAR AND LASER FIELD ANGLES AND RETROREFLECTOR ORIENTATION



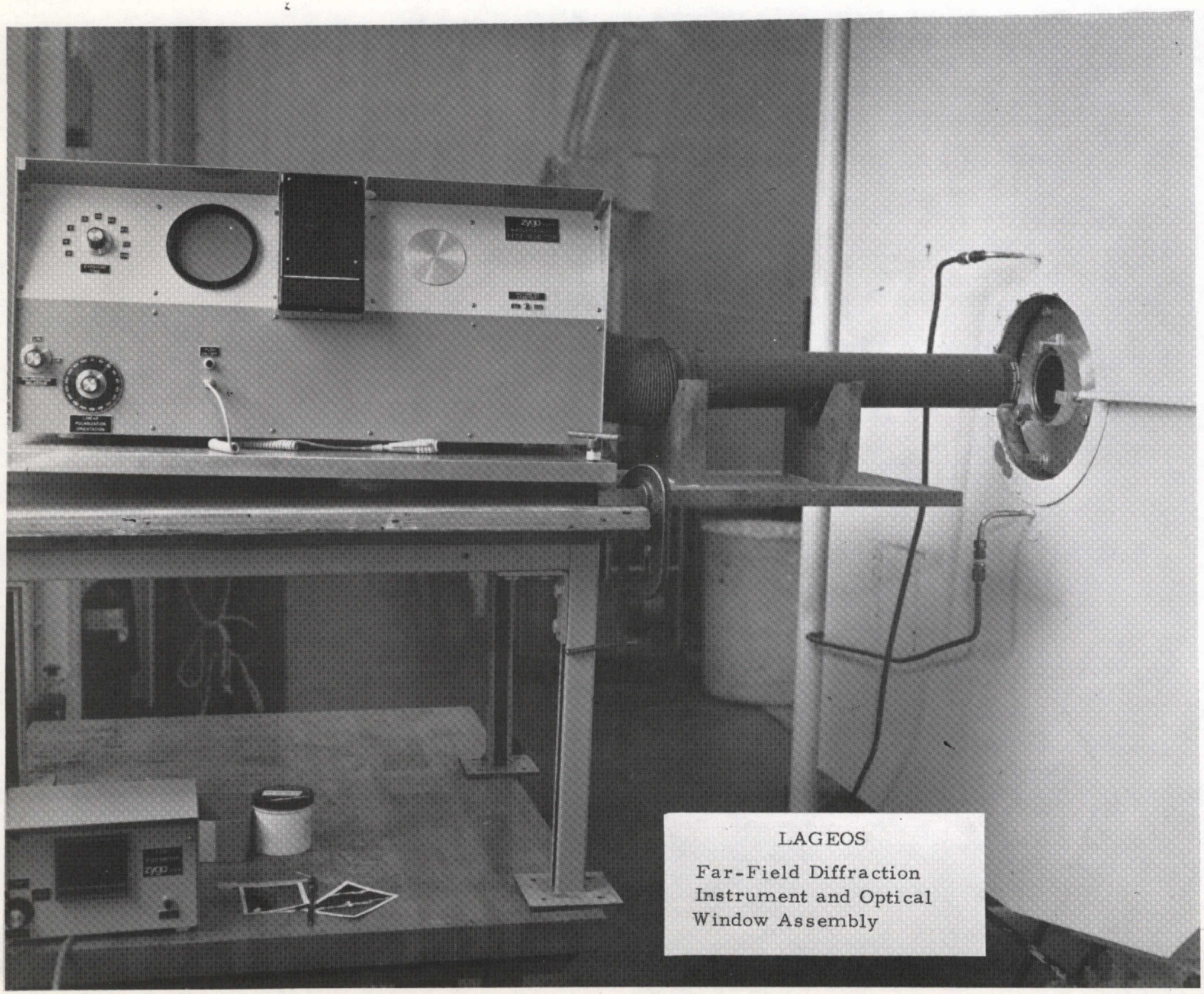
LAGEOS
THERMAL/OPTICAL TEST SET-UP



LAGEOS
Thermal/Vacuum Chamber
& Solar Simulator

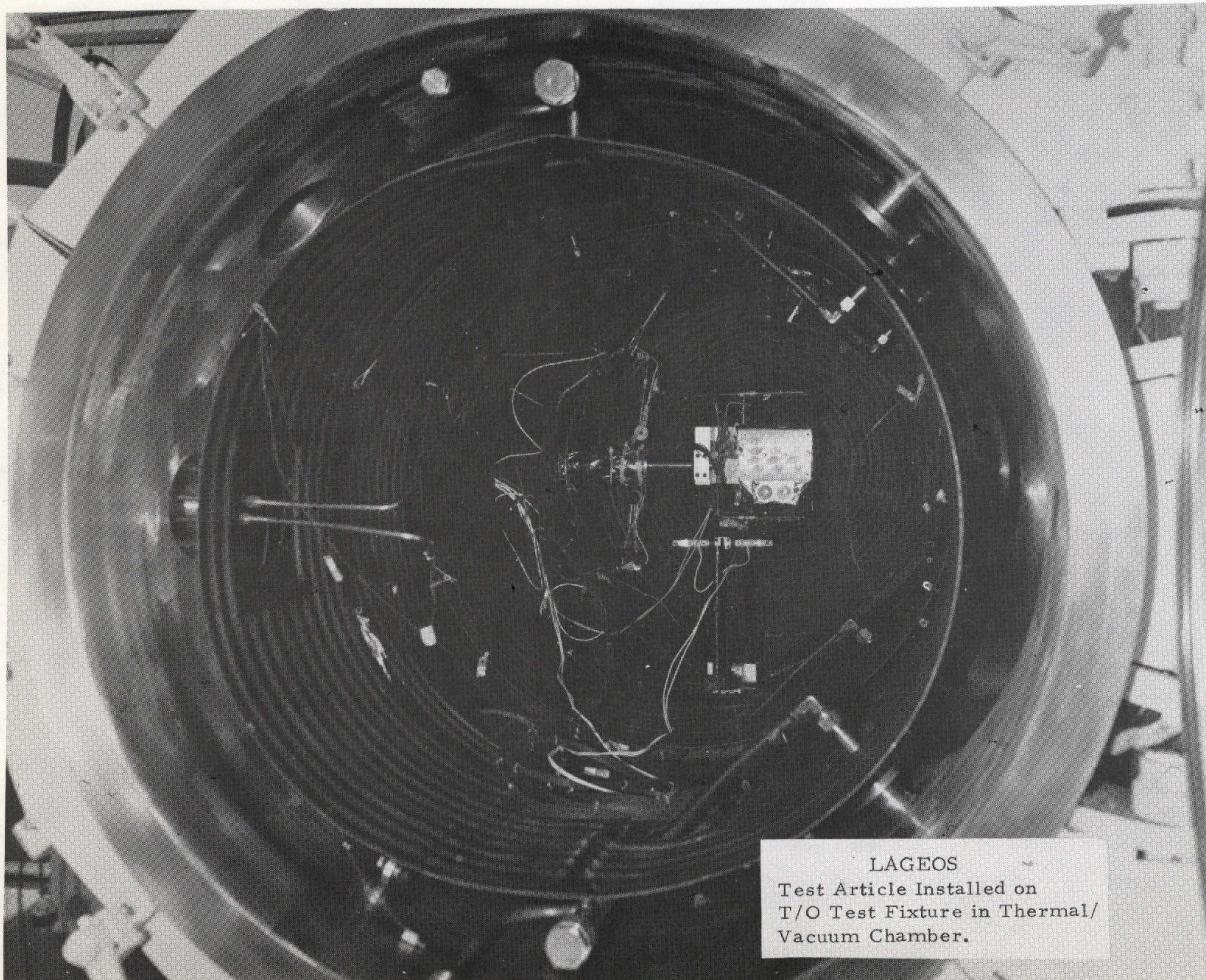


LAGEOS
Data Acquisition System, Power Panel and Test Fixture Manipulator



LAGEOS

Far-Field Diffraction Instrument and Optical Window Assembly



LAGEOS
Test Article Installed on
T/O Test Fixture in Thermal/
Vacuum Chamber.

DESIGN PARAMETERS REPRESENTED IN TEST ARTICLE

- DIRECTLY REPRESENTED:

    RETROREFLECTOR MOUNT DESIGN
    CAVITY DESIGN
    RETROREFLECTOR RECESSION (1 MM)
    RETROREFLECTOR DESIGN
    MOUNT RETAINER RING SURFACE FINISH (BARE, MACHINED ALUMINUM)
    CAVITY INSIDE SURFACE FINISH (BARE, MACHINED ALUMINUM)
    SOLAR HEATING OF RETROREFLECTOR AND MOUNT
    EARTH IR HEATING OF RETROREFLECTOR AND MOUNT

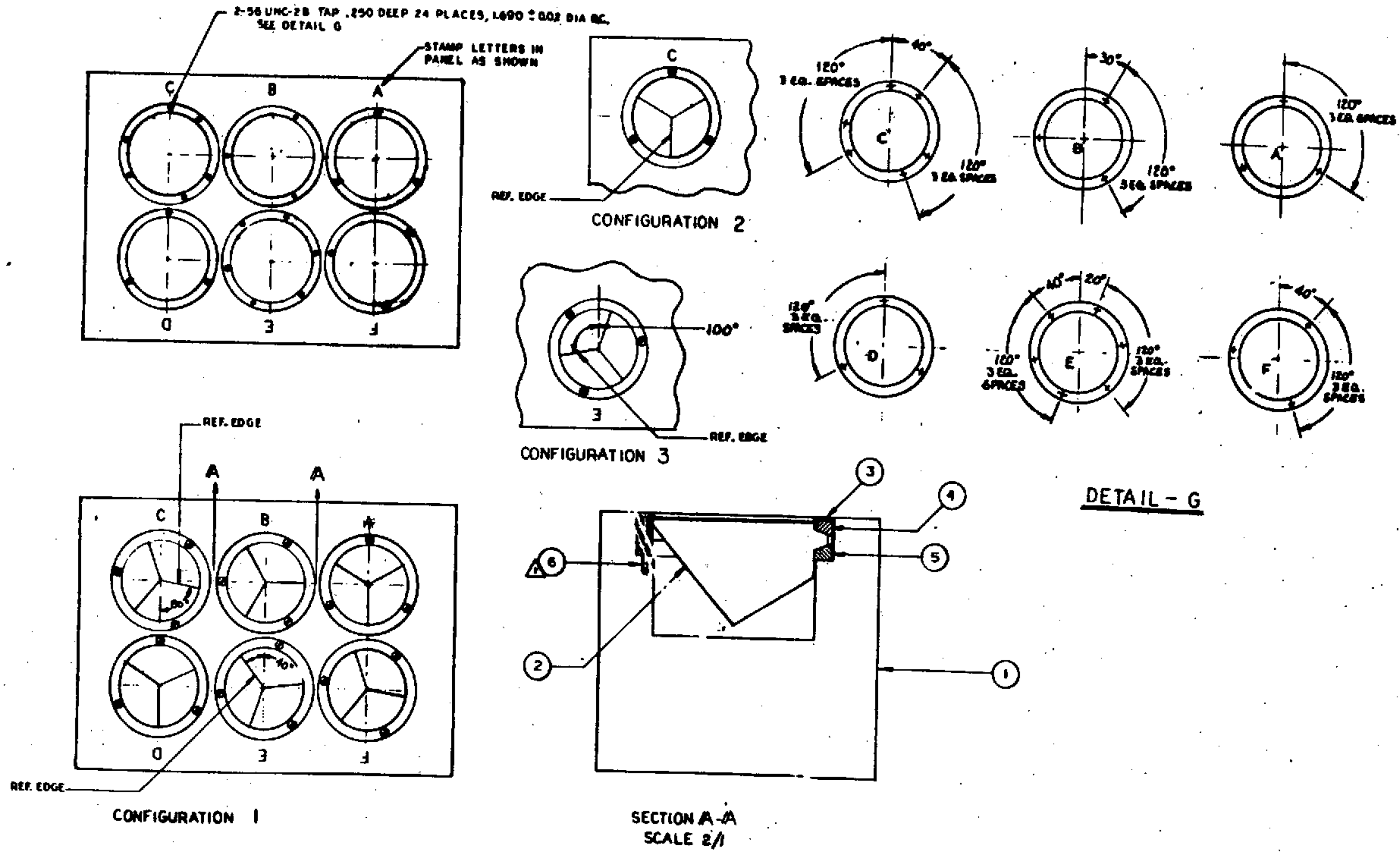
- INDIRECTLY REPRESENTED:

    SATELLITE SPHERICAL SHAPE
    CAVITY PATTERN
    SATELLITE OUTSIDE SURFACE FINISH

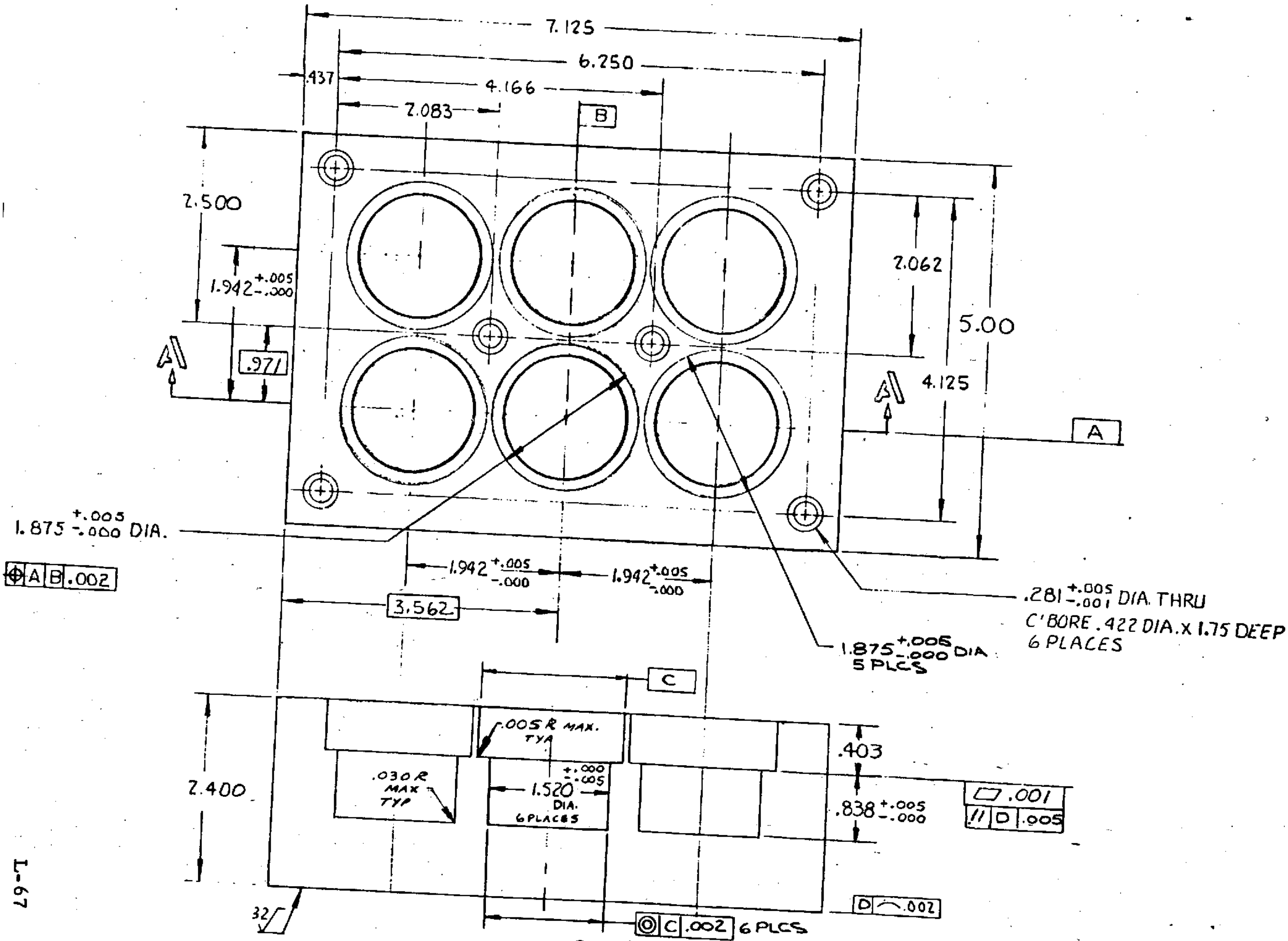
    BY PROVIDING RESULTING CAVITY CORE TEMPERATURE

TEST ARTICLE DESIGN

- PROVIDE, DIRECTLY, DESIGN PARAMETERS WHICH AFFECT RETROREFLECTOR THERMAL/OPTICAL PERFORMANCE.
- PROVIDE MOUNTING FOR SIX (6) LAGEOS RETROREFLECTORS.
- PROVIDE 3 X 2 PATTERN.
- PROVIDE .060 MINIMUM SPACING TO REPRESENT SATELLITE MINIMUM SPACING.
- PROVIDE TIE-DOWN HOLES FOR MOUNTING.
- FABRICATED FROM SAME MATERIAL AS SATELLITE.
- OVERALL SIZE BASED ON EARLY BASELINE; NO CHANGES AFTER TEST FIXTURES WERE DESIGNED.
- SETS OF THREADED HOLES IN CAVITIES TO PROVIDE FOR RETROREFLECTOR ORIENTATIONS.

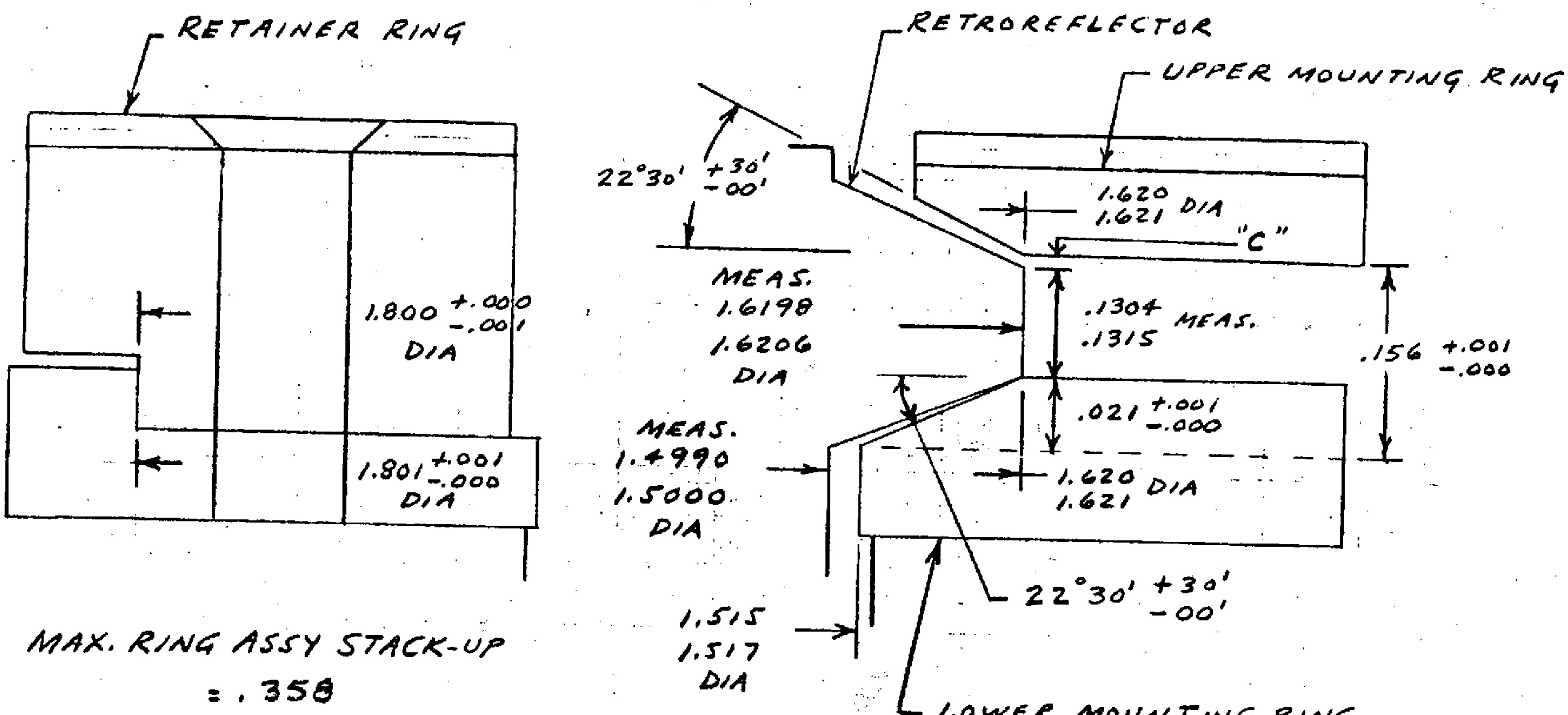


LAGEOS
TEST ARTICLE ASSEMBLY


7.125
6.250
.437
4.166
2.083
B
2.500
1.942 +.005 -.000
.971
2.062
5.00
4.125
A
1.875 +.005 -.000 DIA.
⊕ A B .002
1.942 +.005 -.000
1.942 +.005 -.000
3.562
.281 +.005 -.001 DIA. THRU
C'BORE .422 DIA. x 1.75 DEEP
6 PLACES
1.875 +.005 -.000 DIA
5 PLCS
C
.005 R MAX. TYP
.403
2.400
.030 R MAX TYP
1.520 +.000 -.005 DIA. 6 PLACES
.838 +.005 -.000
.001
// D .005
32
D .002
◎ C .002 6 PLCS

SECTION A-A

LAGEOS
RETROREFLECTOR/RING MOUNT ASSEMBLY



MAX. RING ASSY STACK-UP
= .358

MIN. SCREW LENGTH (MS35202-8)
= .594 - .051 = .543

MIN. ENGAGEMENT WITH TAPPED HOLE IN CAVITY
= .185

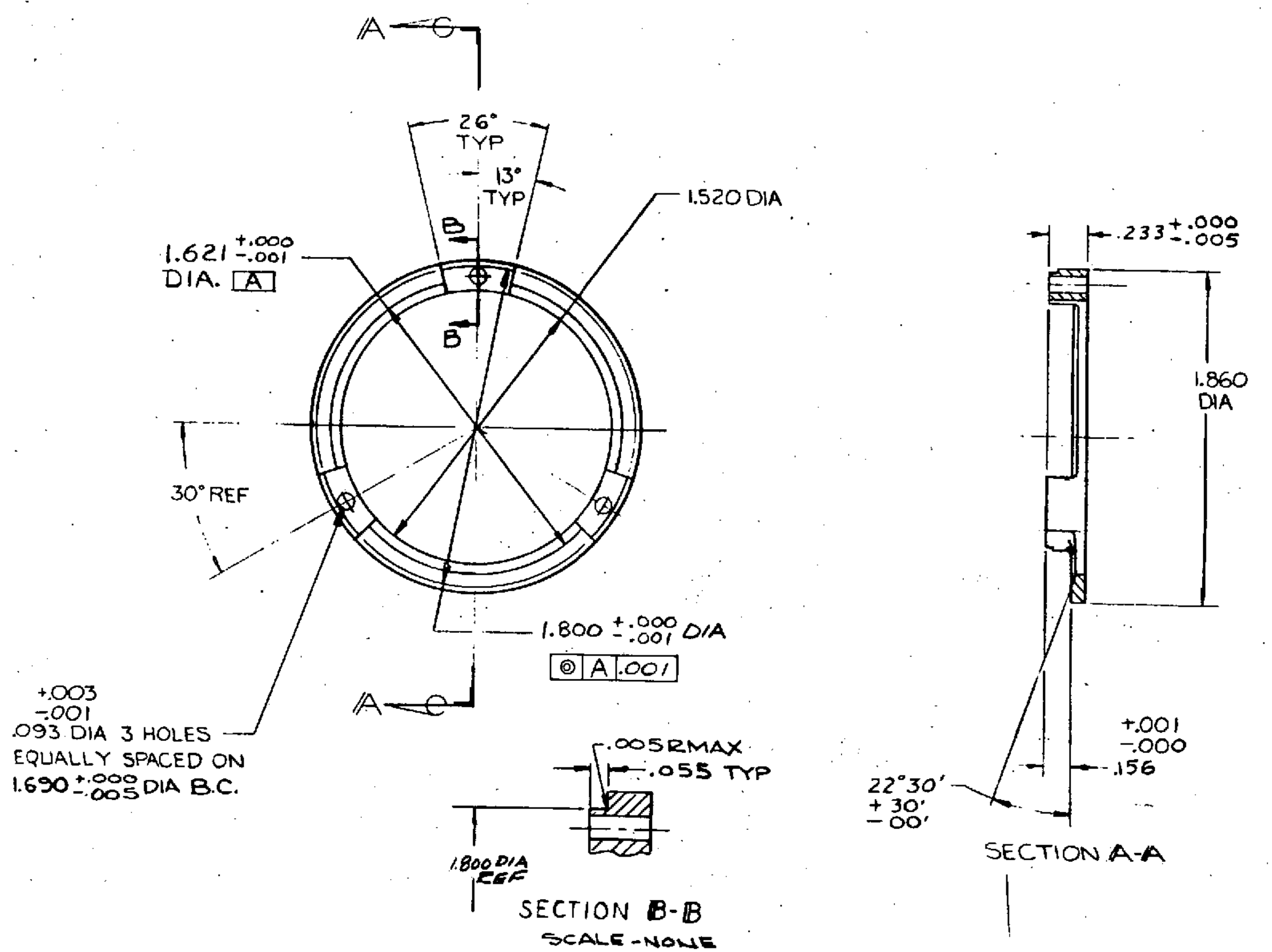
TAB CLEARANCE ("C") VARIES FROM .002 - .006

LAGEOS

UPPER MOUNTING RING

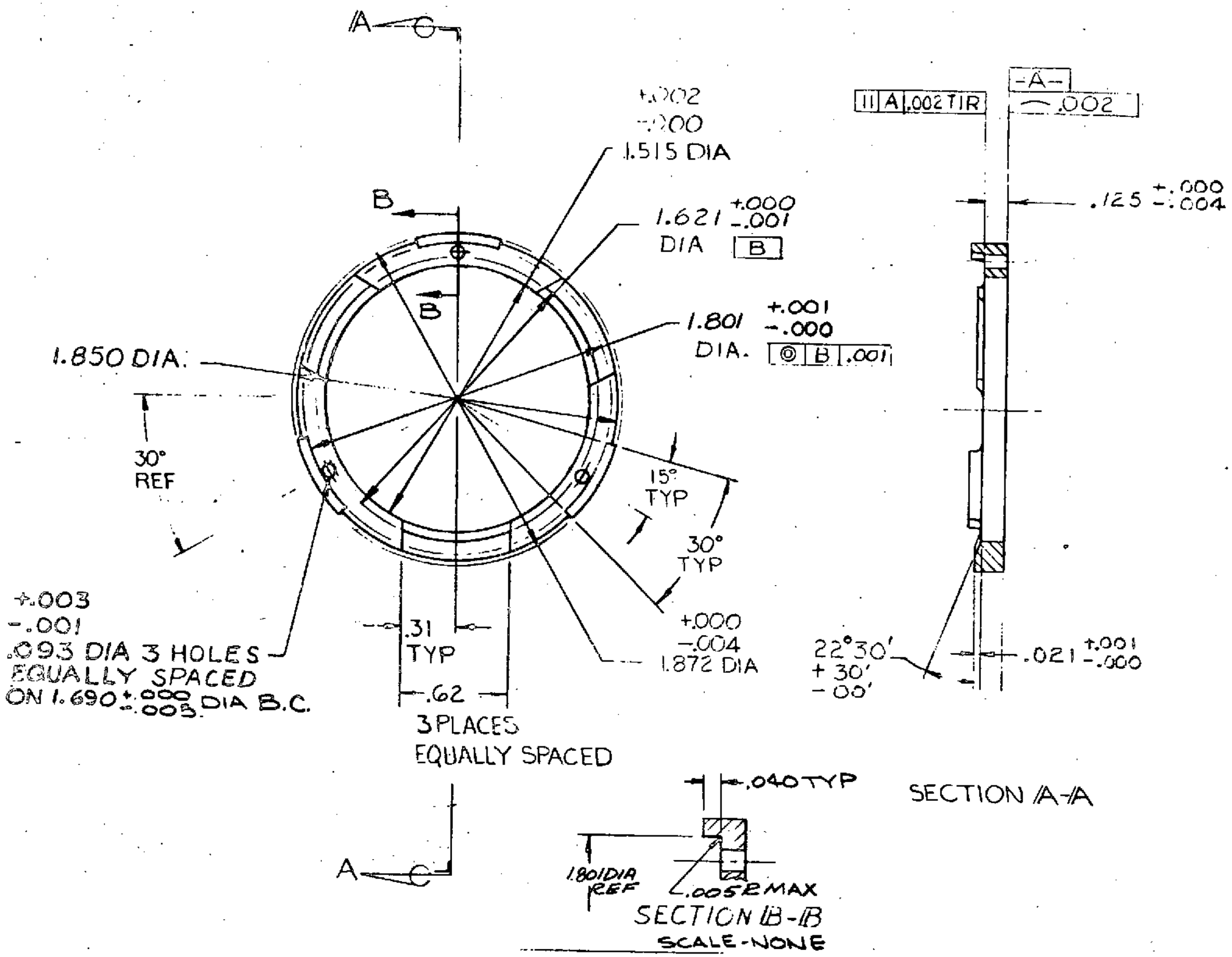
NOTE

1. REMOVE BURRS AND BREAK EDGES .010 MAX
2. ALL BLEND RADII TO BE .062



LAGEOS
LOWER MOUNTING RING

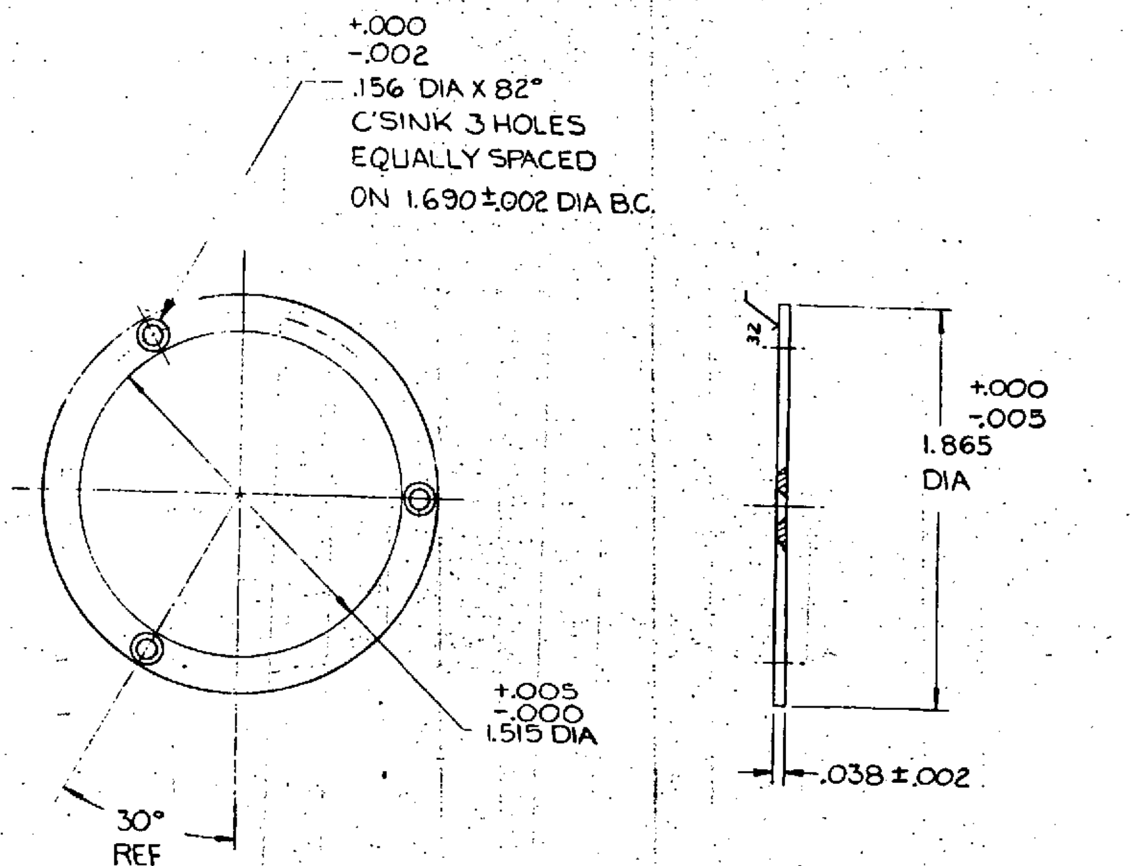
NOTE:
1. REMOVE BURRS AND BREAK EDGES .010 MAX
2. ALL BLEND RADII TO BE .062



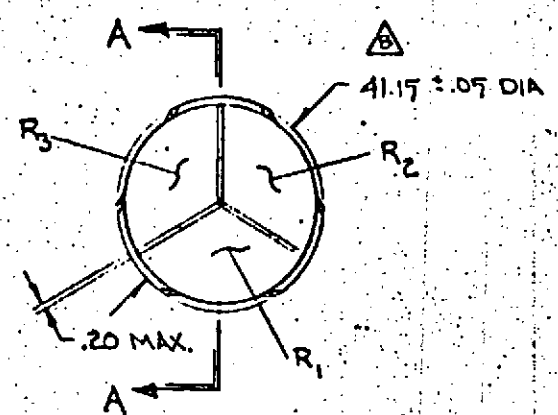
RETAINER RING

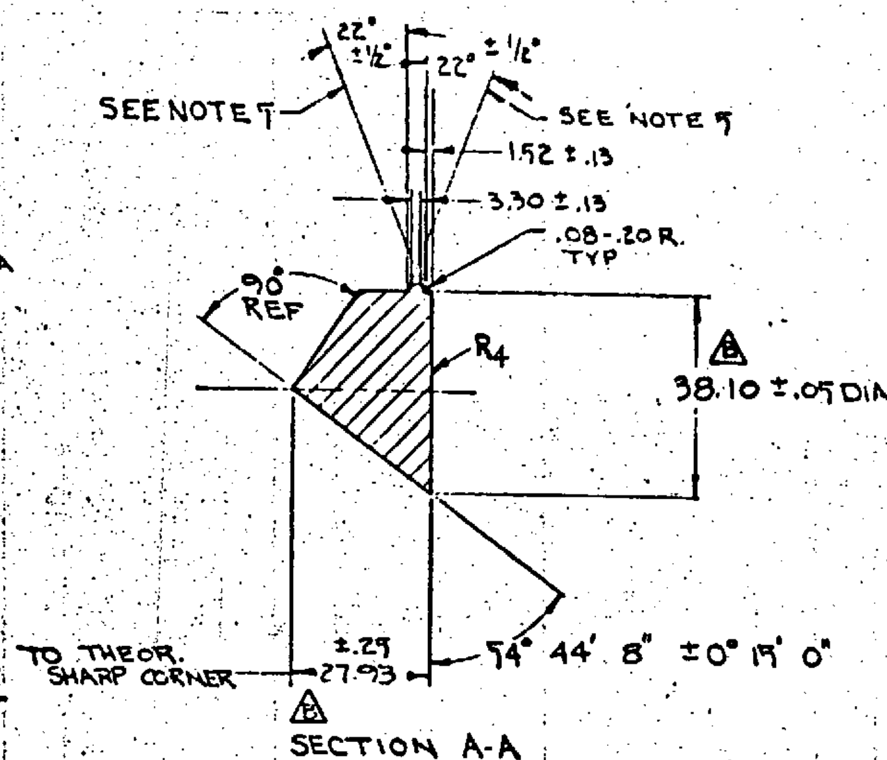
NOTE

1. REMOVE BURRS AND BREAK EDGES .005 MAX



ITEM	RAD	SURFACE
R_1, R_2 & R_3	∞	80-50
R_4	∞	80-50





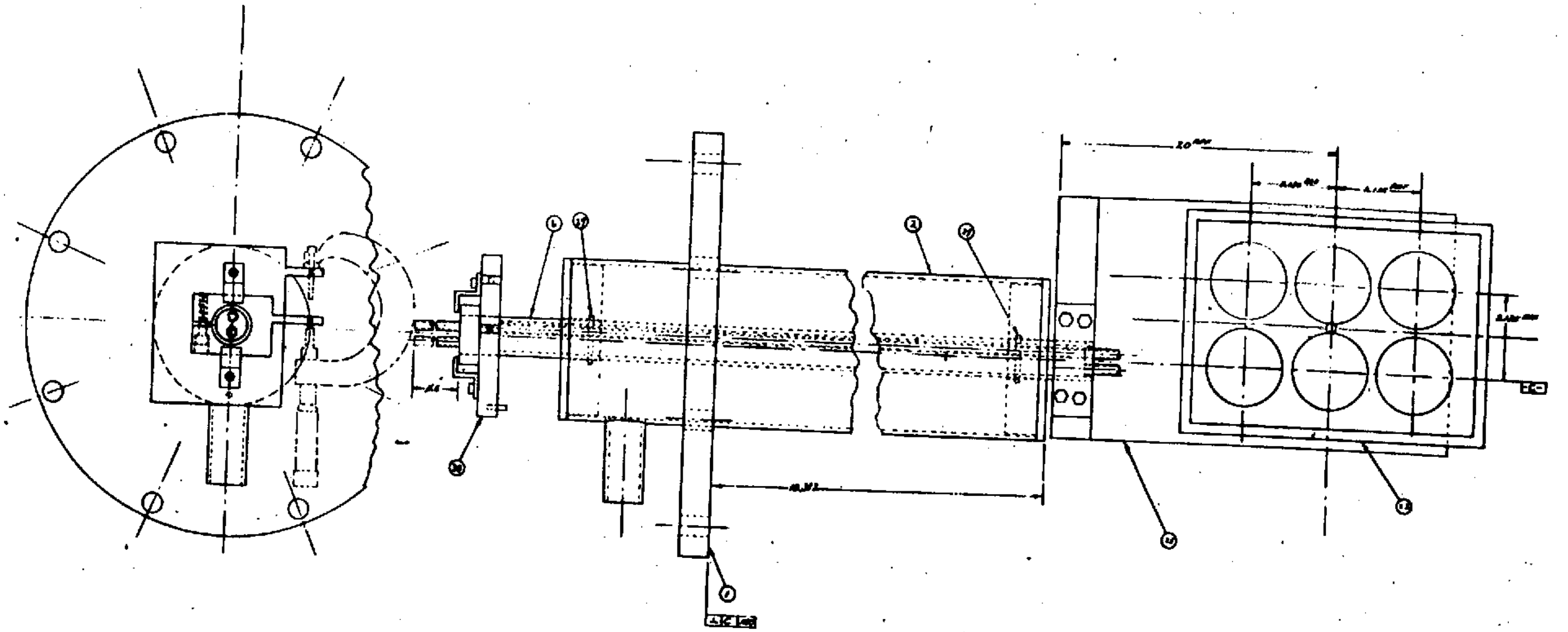
NOTE 1: THREE DIHEDRAL ANGLES TO BE 90° 0' 1.5" ± 0.5"
NOTE 2: 38.10 DIA AND 41.15 DIA TO BE CONCENTRIC TO AXIS WITHIN 0.10 MM T.I.R.
NOTE 3: WAVEFRONT TOLERANCE APPLIES OVER 90% OF FACE AREA
NOTE 4: PROTECTIVE BEVEL ON ALL SHARP EDGES NOT TO EXCEED .20 MM
NOTE 5: SURFACES TO BE SPECULAR FINISH AND COINCIDENT WITH NOMINAL 136° CONICAL SURFACES WITHIN ± .013 MM.
NOTE 6: EXIT WAVEFRONT DISTORTION FOR EACH SEXTANT $\leq \lambda/4$; λ = 632.8 NM

ALL DIMENSIONS IN MM.

LAGEOS Retroreflector

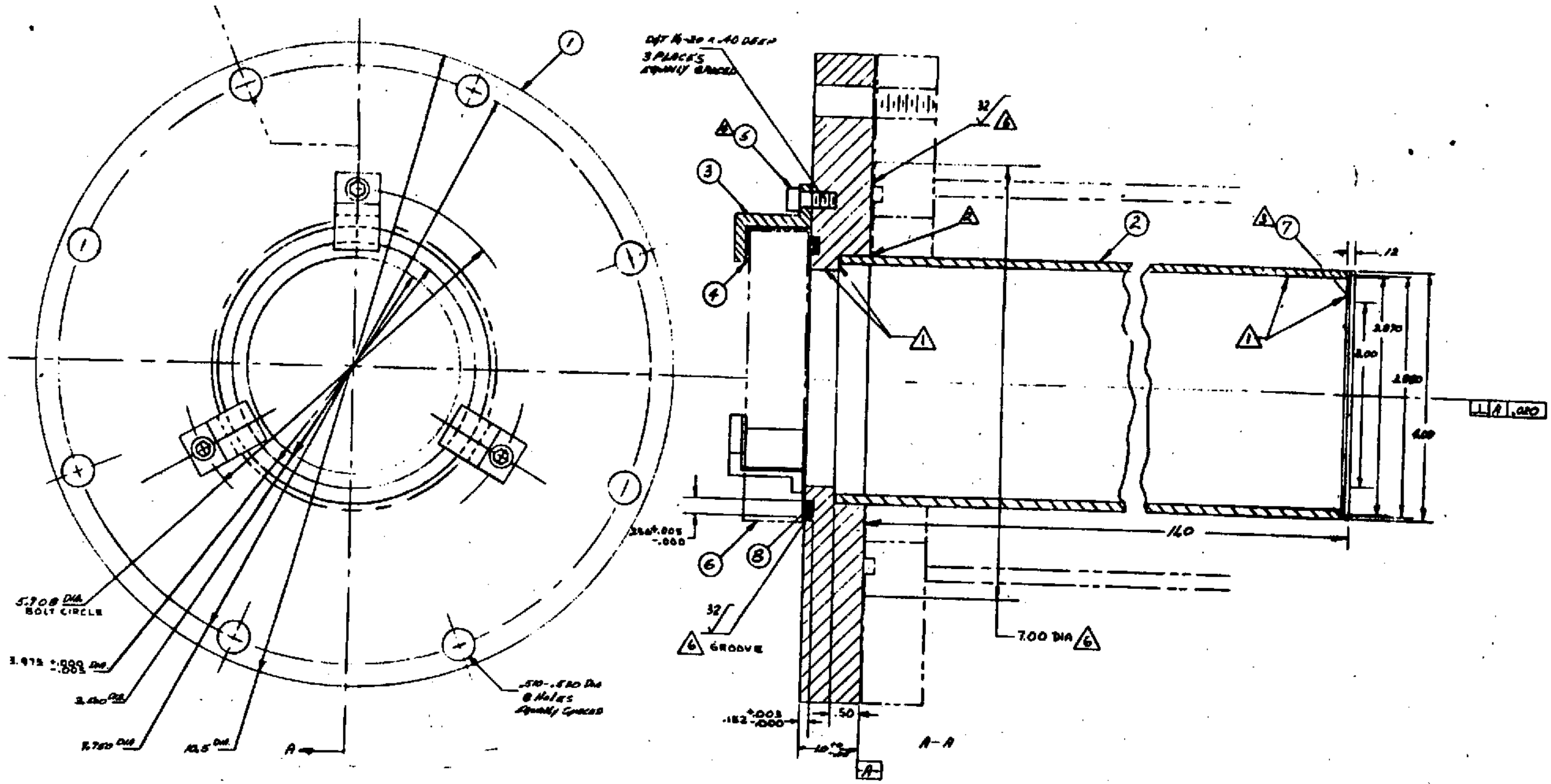
TEST FIXTURE SUMMARY

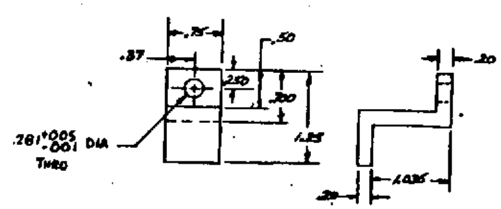
- THERMAL/OPTICAL TEST FIXTURE
- OPTICAL WINDOW AND SHIELD ASSEMBLY
- FAR-FIELD DIFFRACTION INSTRUMENT (DEVELOPED AS BxA CAPTIAL EQUIP.)
- FAR-FIELD DIFFRACTION INSTRUMENT SUPPORT PLATE
- THERMOCOUPLE FIXTURE



LAGEOS

THERMAL/OPTICAL TEST FIXTURE

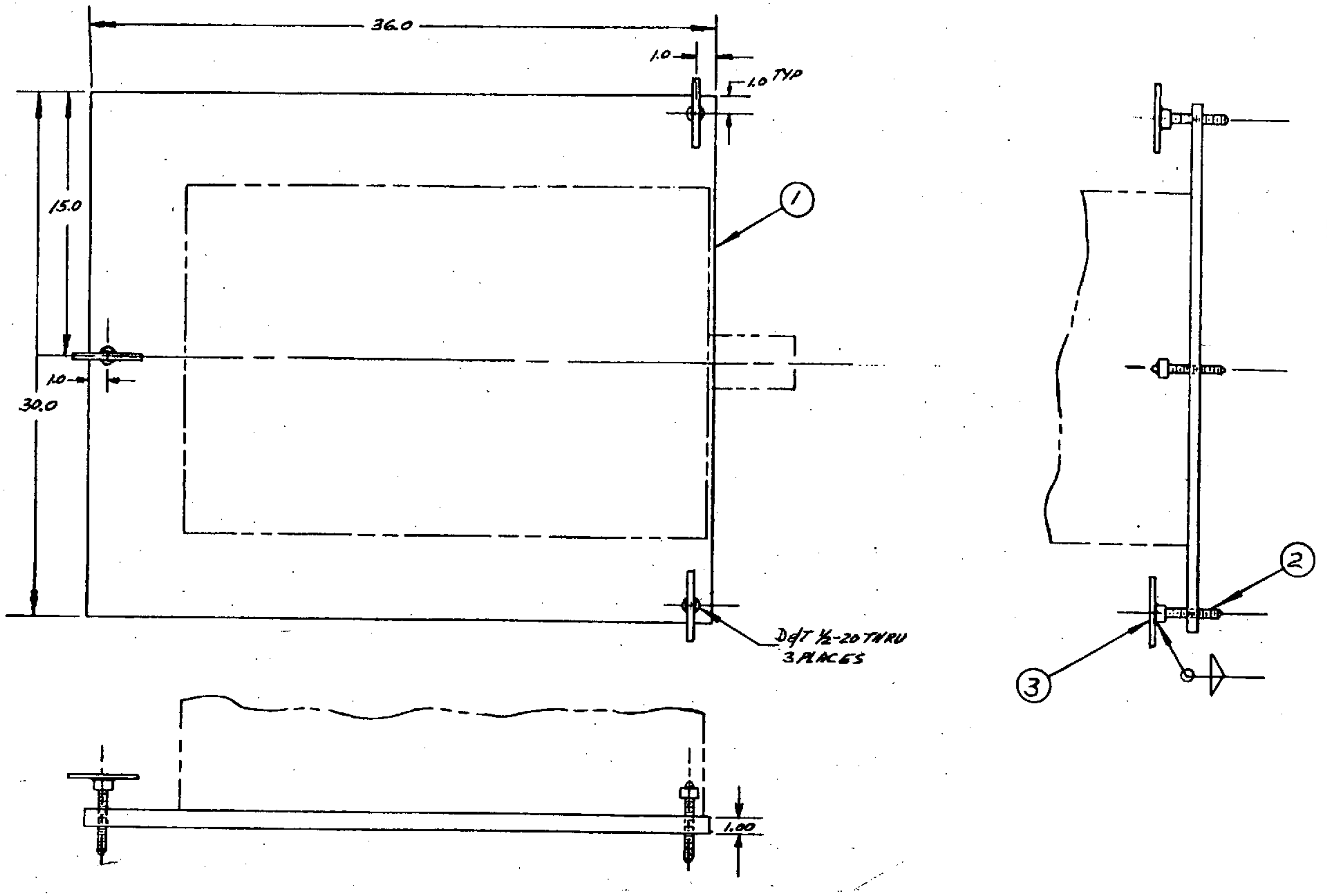




③ WINDOW RETAINER

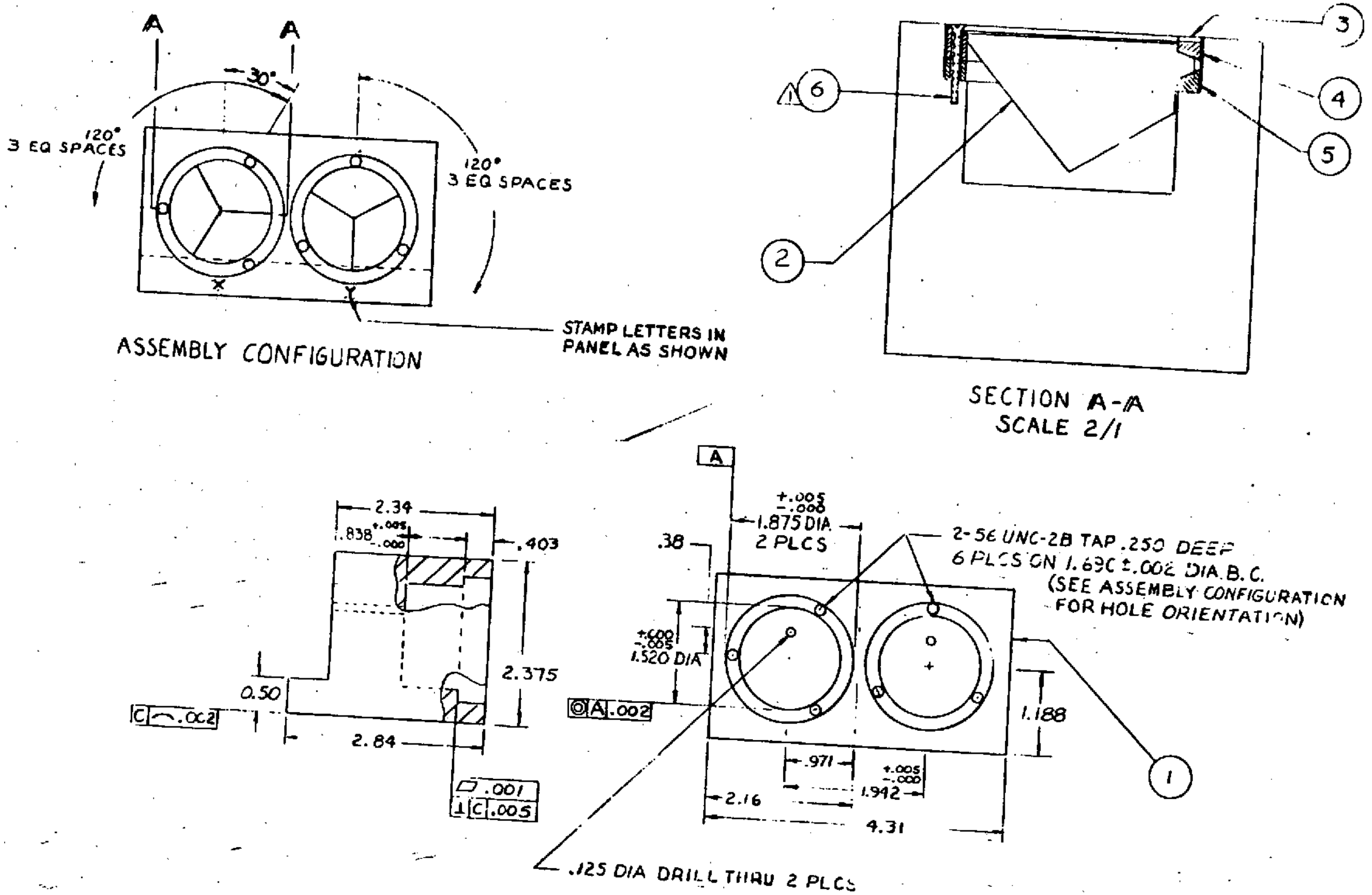
LAGEOS

OPTICAL WINDOW AND SHIELD ASSY.



LAGEOS

FFDI LEVELING PLATE

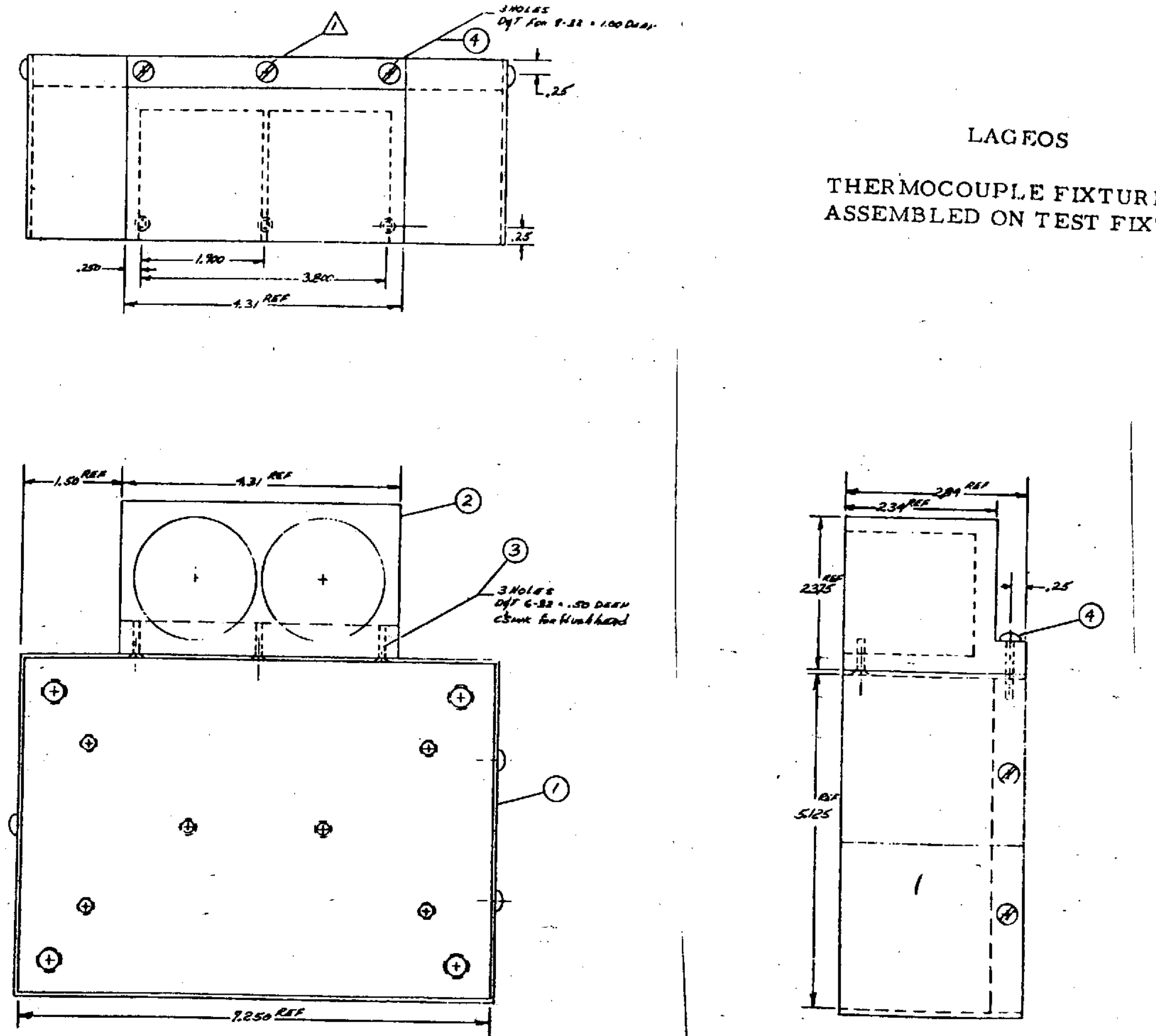


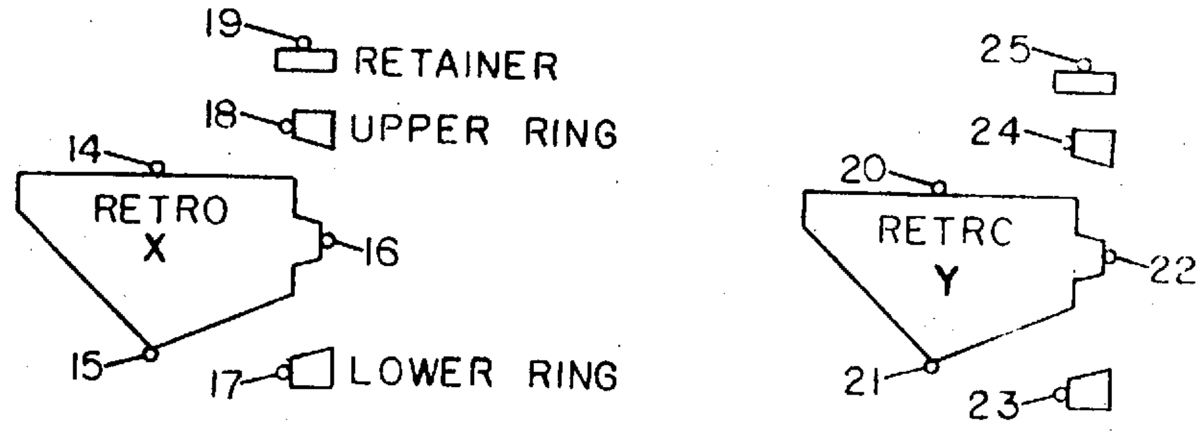
LAGEOS

THERMOCOUPLE FIXTURE

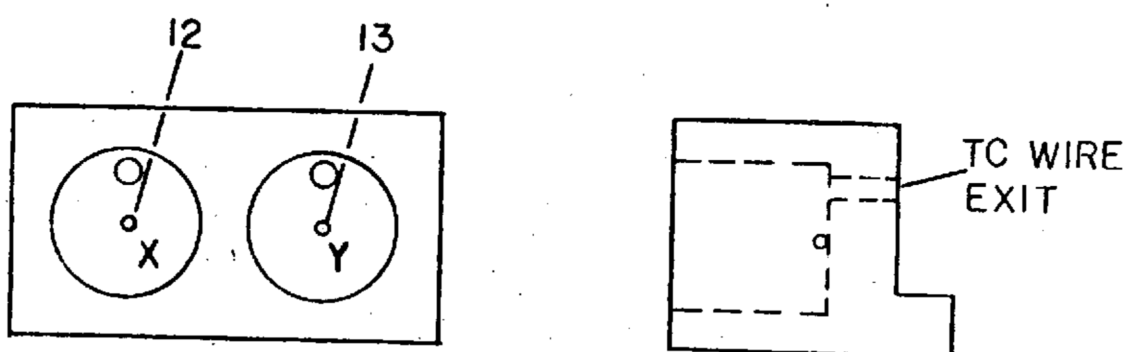
LAGEOS

THERMOCOUPLE FIXTURE
ASSEMBLED ON TEST FIXTURE

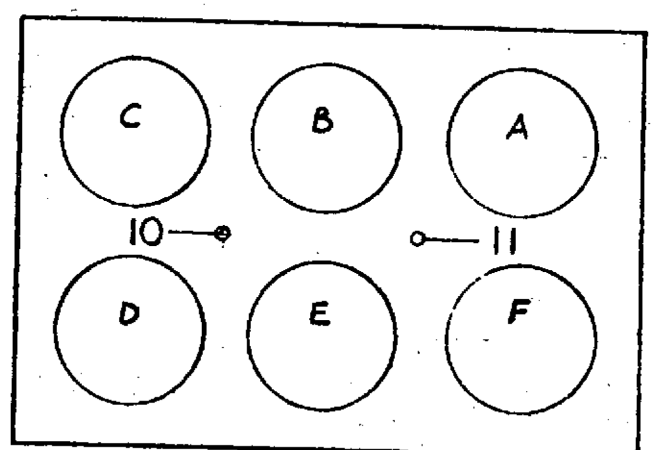




ALSEP RETROREFLECTORS



THERMOCOUPLE FIXTURE



TEST ARTICLE PANEL

THERMOCOUPLE LOCATIONS

FFDI PERFORMANCE REQUIREMENTS

GENERAL

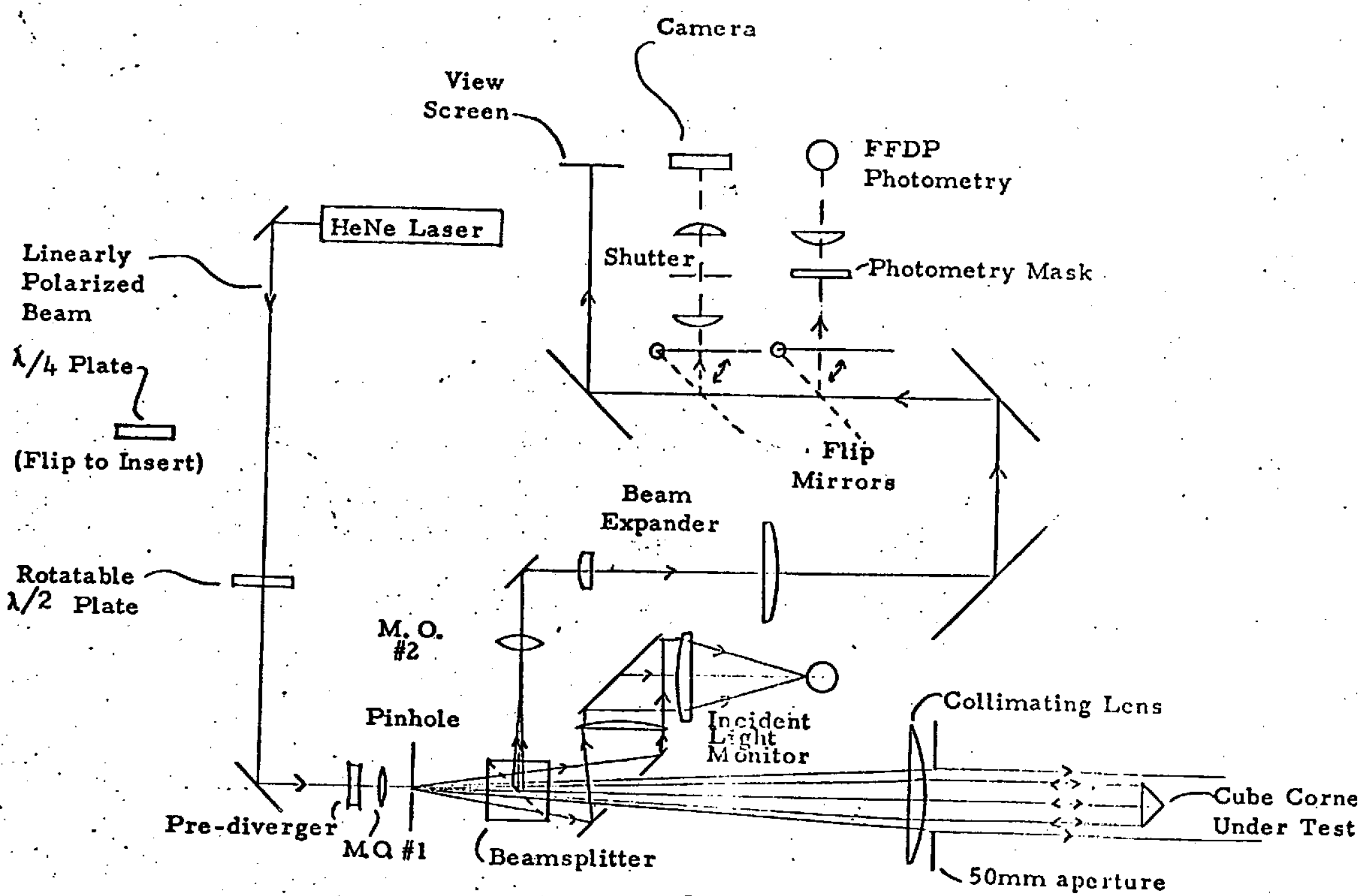
- OPERATE AS THERMAL/VACUUM/OPTICAL TEST INSTRUMENT
- OPERATE AS RETROREFLECTOR INSPECTION INSTRUMENT

OPTICAL

- WAVELENGTH - 6328Å
- BEAM DIAMETER - 50 MILLIMETERS OR GREATER
- BEAM UNIFORMITY - LESS THAN 20 PERCENT VARIATION
- WAVEFRONT QUALITY - BETTER THAN $\lambda/10$
- POLARIZATION - LINEAR OR CIRCULAR

MEASUREMENT OUTPUTS

- VIEW SCREEN
- POLAROID CAMERA
- PHOTOMETRIC MEASUREMENTS - RELATIVE ENERGY IN FAR FIELD TO ± 5 PERCENT
  TOTAL ENERGY IN PATTERN
  ENERGY IN SELECTED ANNULUS



FFDI

Optical Schematic

LAGEOS

FFDI MEASUREMENTS OUTPUT

VISUAL - VIEW SCREEN PROVIDES FAR-FIELD DIFFRACTION PATTERN DISPLAY; FIELD OF VIEW IS 75 ARC SEC

PHOTOGRAPHIC - POLAROID CAMERA PROVIDES PHOTOGRAPH OF THE FAR-FIELD DIFFRACTION PATTERN: EXPOSURE VARIABLE FROM 1/4 TO 1/500 SEC

PHOTOMETRIC - DIGITAL DISPLAY (SELECTED)
- INCIDENT LIGHT MONITOR
- RETURN LIGHT (IN FAR-FIELD) MEASUREMENT
- RATIO OF MEASUREMENT-TO-MONITOR

SENSITIVITY SELECTOR
- X1
- X10

MASK HOLDER

ANNULUS - 13.2 TO 16.9 ARC SEC DIAMETERS
FULL FIELD - 107.5 ARC SEC DIAMETER
HALF ANNULUS - 15.2 TO 16.9 ARC SEC DIAMETERS

POLARIZATION SELECTION - LINEAR OR CIRCULAR
ANGULAR ORIENTATION OF LINEAR POLARIZATION

LAGEOS

OPTICAL TEST DATA REDUCTION

<u>DIGITAL DISPLAY:</u> LASER - INCIDENT LIGHT MONITOR
FFDP - RETURN LIGHT (INF AR-FIELD) MEASUREMENT
FFDP/LASER - RETURN RATIO (INDEPENDENT OF LASER OUTPUT VARIATIONS)

<u>RECORDED DATA:</u>

RATIO-ANNULAR RETURN = (FFDP/LASER) WITH 13.2 TO 16.9 ARC SEC ANNULUS MASK INSTALLED
RATIO-FULL FIELD RETURN = (FFDP/LASER) WITH 107.5 ARC SEC MASK INSTALLED

<u>REDUCED DATA:</u>

$$\text{PERFORMANCE RATIO} = \text{ANNULAR RETURN-TO-FULL FIELD RATIO} = \frac{\text{(RATIO-ANNULAR RETURN)} @ \alpha}{\text{(RATIO-FULL FIELD RETURN)} @ \alpha = 0}$$

$$\frac{\text{(PERFORMANCE RATIO) @ CAVITY TEMPERATURE}}{\text{(PERFORMANCE RATIO) @ ISOTHERMAL-VACUUM}} = \frac{\left[\dfrac{\text{(RATIO-ANNULAR RETURN)} @ \alpha}{\text{(RATIO-FULL FIELD RETURN)} @ \alpha = 0}\right] \text{@ CAVITY TEM.}}{\left[\dfrac{\text{(RATIO-ANNULAR RETURN)} @ \alpha}{\text{(RATIO-FULL FIELD RETURN)} @ \alpha = 0}\right] \text{@ ISO-VACUUM}}$$

$$\frac{\text{(RATIO-ANNULUS) @ CAVITY TEMPERATURE}}{\text{(RATIO-ANNULUS) @ ISOTHERMAL-VACUUM}} = \frac{\left[\text{(RATIO-ANNULAR RETURN)} @ \alpha\right] \text{@ CAVITY TEMP.}}{\left[\text{(RATIO-ANNULAR RETURN)} @ \alpha\right] \text{@ ISO-VACUUM}}$$

FOR COMPARISON WITH OPTICAL ANALYSIS RESULTS:

$$\text{RELATIVE ANNULAR RETURN} = \left[\frac{\text{(RATIO-ANNULAR RETURN)} @ \alpha}{\text{(RATIO-FULL FIELD RETURN)} @ \alpha}\right] \text{@ CAVITY TEMP.}$$

LAGEOS

FFDI SCALE FACTOR DETERMINATION

- CALIBRATION RETROREFLECTOR
  - FABRICATED TO PROVIDE A FAR-FIELD DIFFRACTION PATTERN CONSISTING OF TWO SPOTS SEPARATED BY 11.1 ARC SEC. (BACK FACES ARE SILVERED)
  - SEPARATION DETERMINED INDEPENDENTLY BY TWYMAN-GREEN INTERFEROGRAM
  - BASED ON PHOTOGRAPHIC MEASUREMENT, SCALE FACTOR IS 1.47 ARC SEC/MM

- ALTERNATE METHOD
  - MEASURE DIAMETER OF FIRST DARK RING OF AIRY PATTERN FOR MASTER 90° RETROREFLECTOR AND AN APERTURE, OF A KNOWN DIAMETER, IN THE LASER BEAM
  - ANGULAR DIAMETER ϕ = 2.44 λ/D RADIANS

    where λ = 632.8 NM

    D = APERTURE DIAMETER

PHOTO: 118
EXPOSURE: 1/500 SEC
TEST NO. 18

LAGEOS RETROREFLECTOR CHARACTERISTICS

TEST LOCATION		A	B	C	D	E	F
SERIAL NO.		3	5	6	1	4	2
WAVEFRONT DEVIATION							
SECTOR	1	0.15 λ	0.10 λ	0.10 λ	0.20 λ	0.20 λ	0.20 λ
	2	0.15	0.20	0.12	0.15	0.10	0.15
	3	0.10	0.10	0.10	0.10	0.20	0.17
	4	0.10	0.10	0.10	0.12	0.15	0.20
	5	0.10	0.10	0.10	0.10	0.15	0.10
	6	0.10	0.10	0.15	0.15	0.20	0.20
DIHEDRAL* ANGLES (ARC SEC)							
$R_1 - R_2$		1.81	2.07	1.30	2.00	2.00	2.05
$R_2 - R_3$		1.08	1.90	1.00	0.92	1.60	1.54
$R_3 - R_1$		1.42	1.80	1.16	1.24	1.57	1.83
DIAMETER OF ANNULUS CENTROID (ARC SEC)**		17.6	23.5	18.4	22.0	20.6	19.8

*90° + Angle Tabulated

**Based on Far-Field Pattern Photograph Measurement

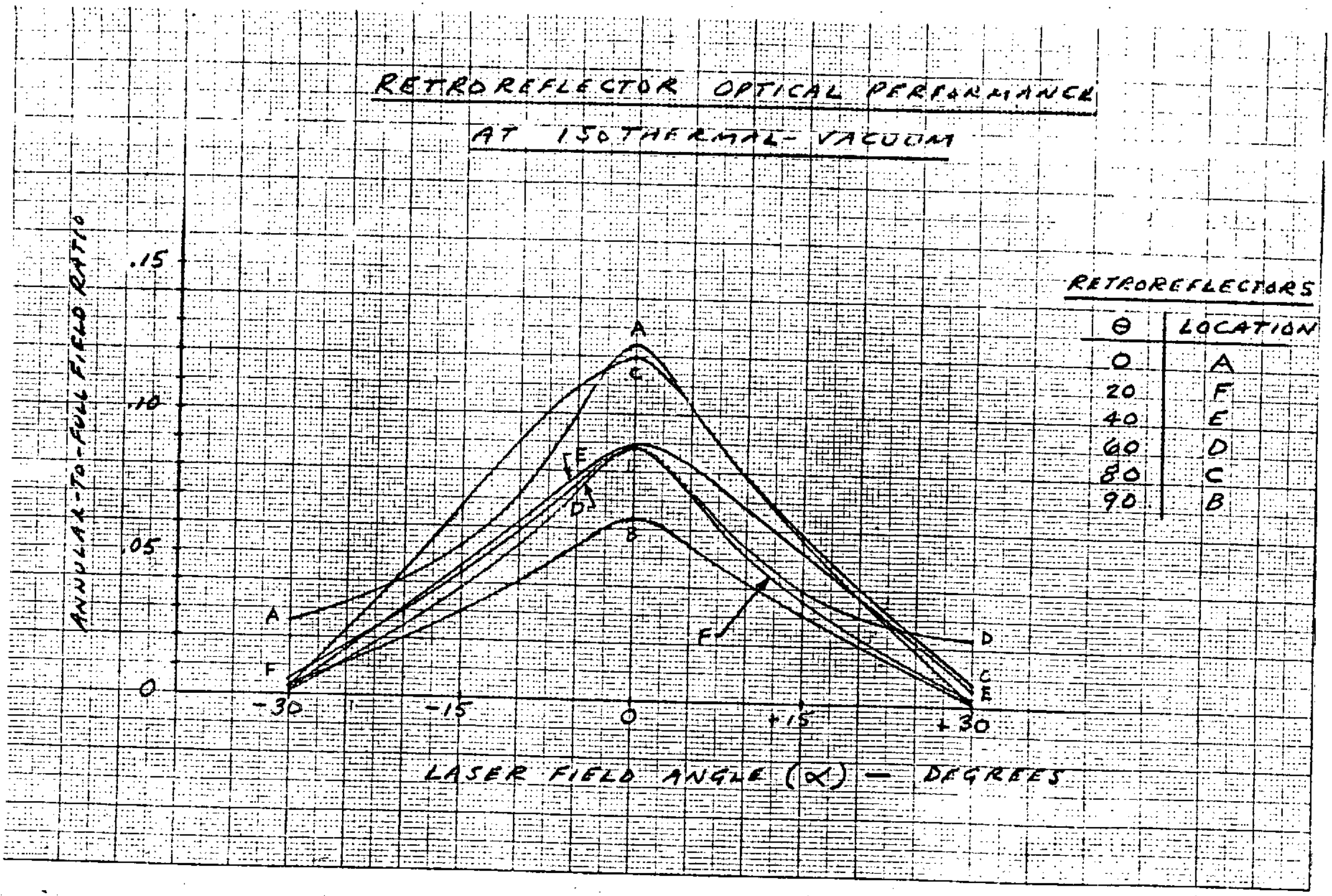
RETROREFLECTOR OPTICAL PERFORMANCE AT ISOTHERMAL-AMBIENT CONDITIONS

ANNULAR RETURN-TO-FULL FIELD RETURN* RATIO

	TEST LOCATION	A	B	C	D	E	E	F
	ORIENTATION (θ) -DEGREES	0	90	80	60	40	100	20
LASER INCIDENT ANGLE (α) - DEGREES	+30	.002**	.002	.007	.017**	X	.003	.001
	+15	.056**	.030**	.057	.038**	.050	.054**	.031
	0	.118**	.060**	.117**	.098**	.106	.102**	.084**
	-15	.052**	.032	.070	.038**	X	.046	.044
	-30	.026**	.004	.004	.002**	X	.007	.007

* FULL FIELD RETURN = MEASURED VALUE AT $\alpha = 0°$

** AVG. VALUES, TWO TESTS

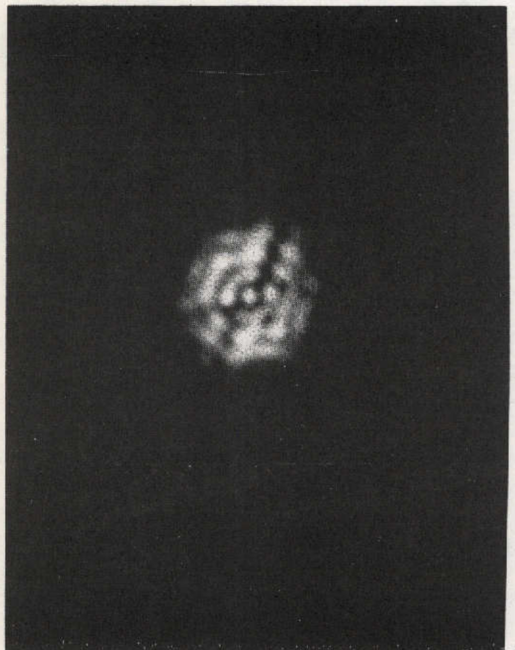


RETROREFLECTOR OPTICAL PERFORMANCE
AT 15° THERMAL-VACUUM
ANNULAR-TO-FULL FIELD RATIO
.15
.10
.05
0
-30
-15
0
+15
+30
LASER FIELD ANGLE (α) — DEGREES
A
C
E
D
B
F
RETROREFLECTORS
θ LOCATION
0 A
20 F
40 E
60 D
80 C
90 B

PHOTOGRAPHIC RESULTS

ISOTHERMAL-VACUUM (TEST NO. 17)

LASER INCIDENT ANGLE
$\alpha = 0°$

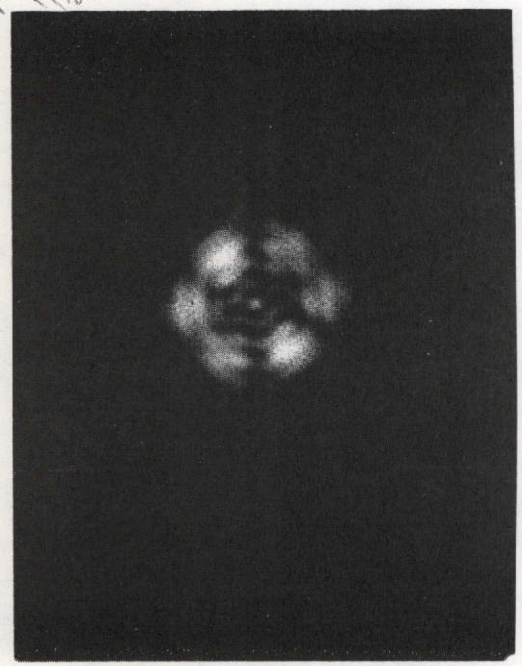


32

RETROREFLECTOR A

$\frac{\text{RATIO ANNULAR}}{\text{RATIO FULL FIELD}} = .124$

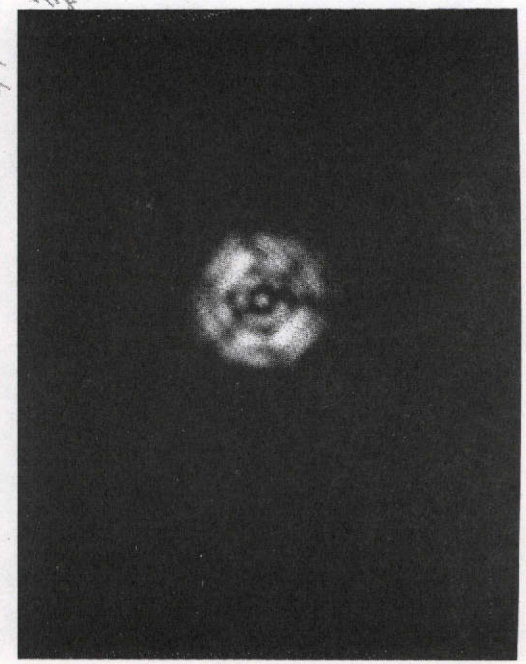
42 1/250



RETROREFLECTOR B

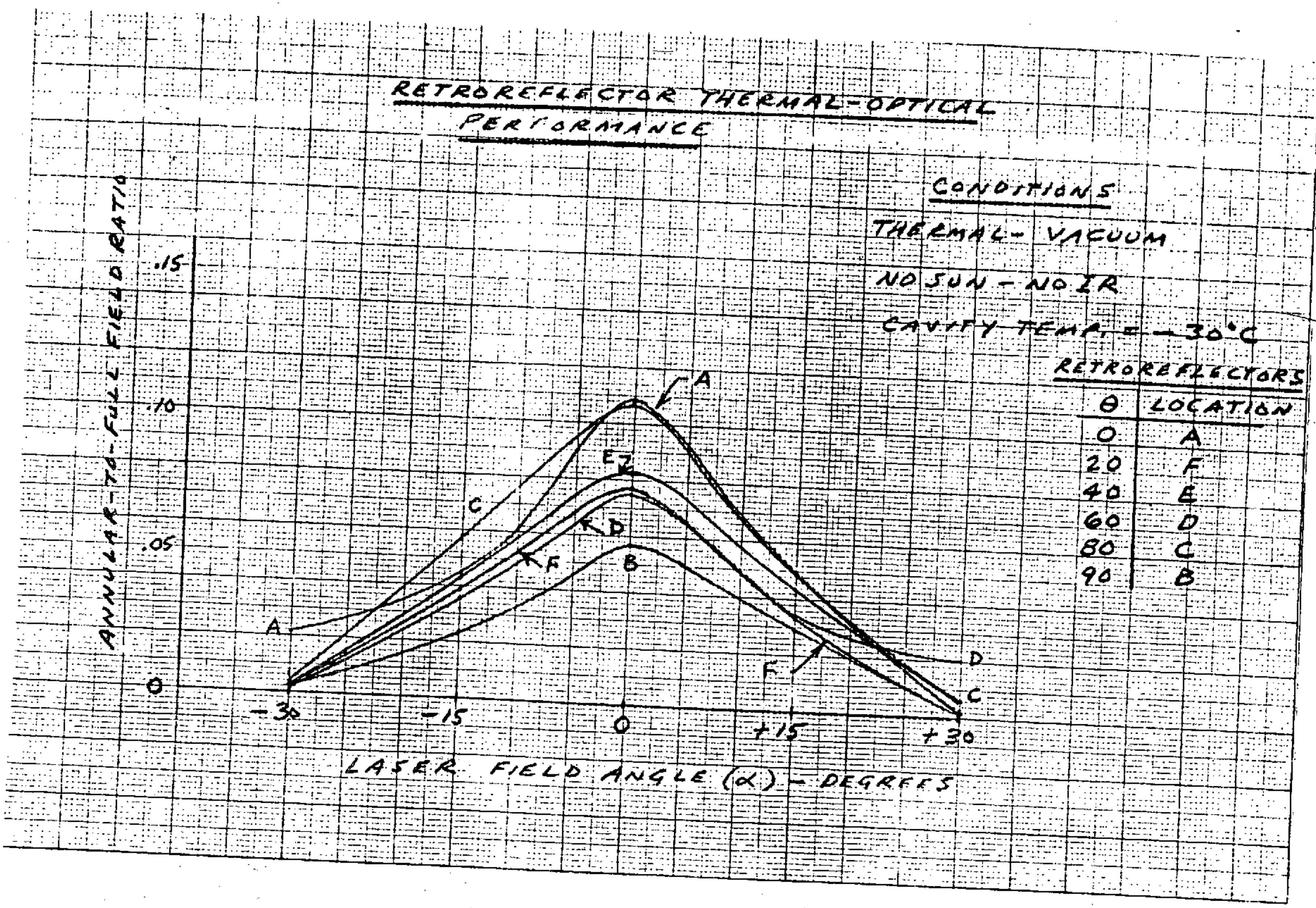
$\frac{\text{RATIO ANNULAR}}{\text{RATIO FULL FIELD}} = .067$

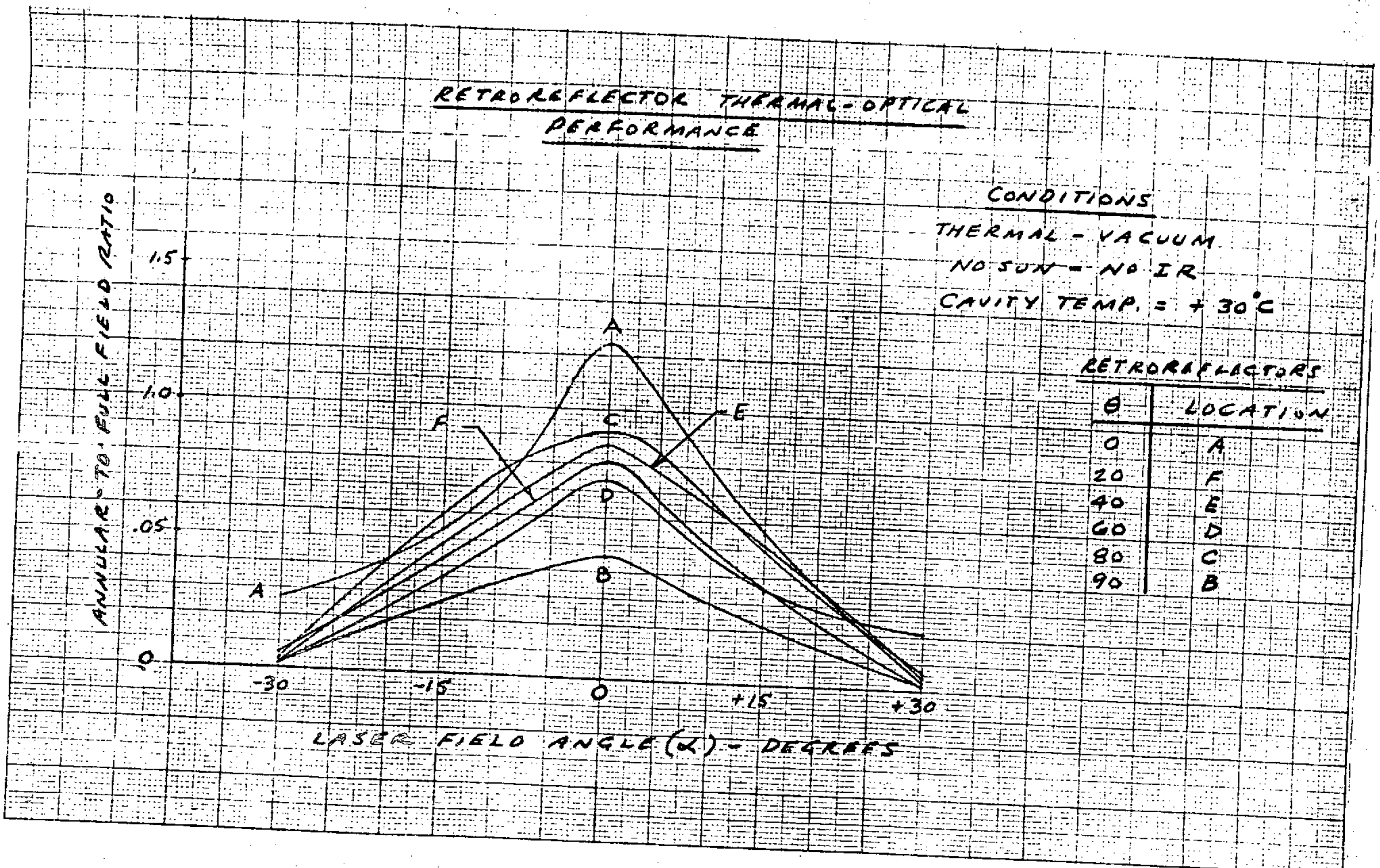
47 1/250



RETROREFLECTOR C

$\frac{\text{RATIO ANNULAR}}{\text{RATIO FULL FIELD}} = .127$

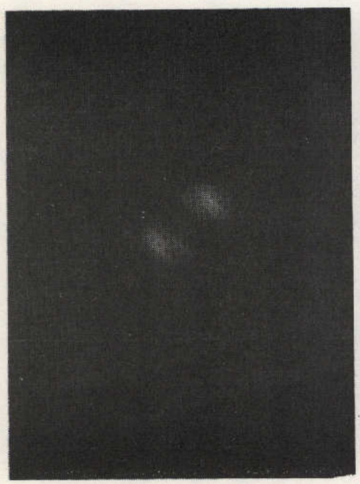

RETROREFLECTOR THERMAL-OPTICAL PERFORMANCE
CONDITIONS
THERMAL- VACUUM
NO SUN - NO IR
CAVITY TEMP. = -30°C
RETROREFLECTORS
θ LOCATION
0 A
20 F
40 E
60 D
80 C
90 B
ANNULAR-TO-FULL FIELD RATIO
.15
.10
.05
0
-30
-15
0
+15
+30
LASER FIELD ANGLE (α) - DEGREES
A
B
C
D
E
F


RETROREFLECTOR THERMAL-OPTICAL PERFORMANCE
CONDITIONS
THERMAL - VACUUM
NO SUN - NO IR
CAVITY TEMP. = + 30°C
RETROREFLECTORS
θ | LOCATION
0 | A
20 | F
40 | E
60 | D
80 | C
90 | B
ANNULAR TO FULL FIELD RATIO
1.5
1.0
.05
0
-30
-15
0
+15
+30
LASER FIELD ANGLE (α) - DEGREES
A
C
D
B
E
F

PHOTOGRAPHIC RESULTS

NO SUN - NO IR (TEST NO. 3)

+30°C CAVITY CORE TEMPERATURE

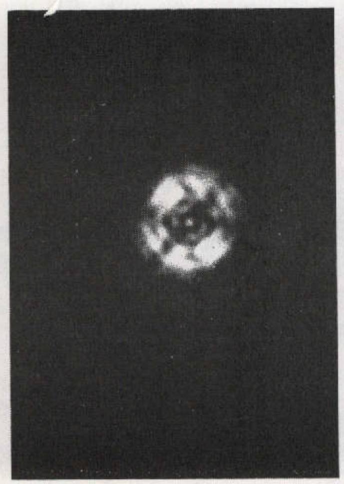


α = -30°
EXPOSURE: 1/30 SEC

$\frac{\text{RATIO ANNULAR}}{\text{(RATIO FULL FIELD)}}$ = .004

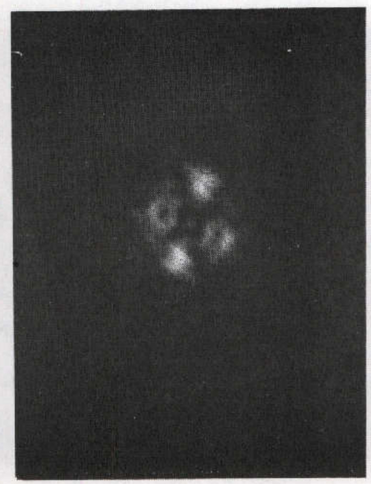
α = -15°
EXPOSURE: 1/250 SEC

$\frac{\text{RATIO ANNULAR}}{\text{(RATIO FULL FIELD)}}$ = .060



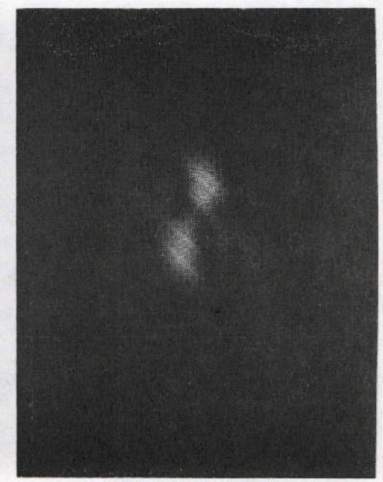
α = 0°
EXPOSURE: 1/250 SEC

$\frac{\text{RATIO ANNULAR}}{\text{(RATIO FULL FIELD)}}$ = .092



α = +15°
EXPOSURE: 1/250 SEC

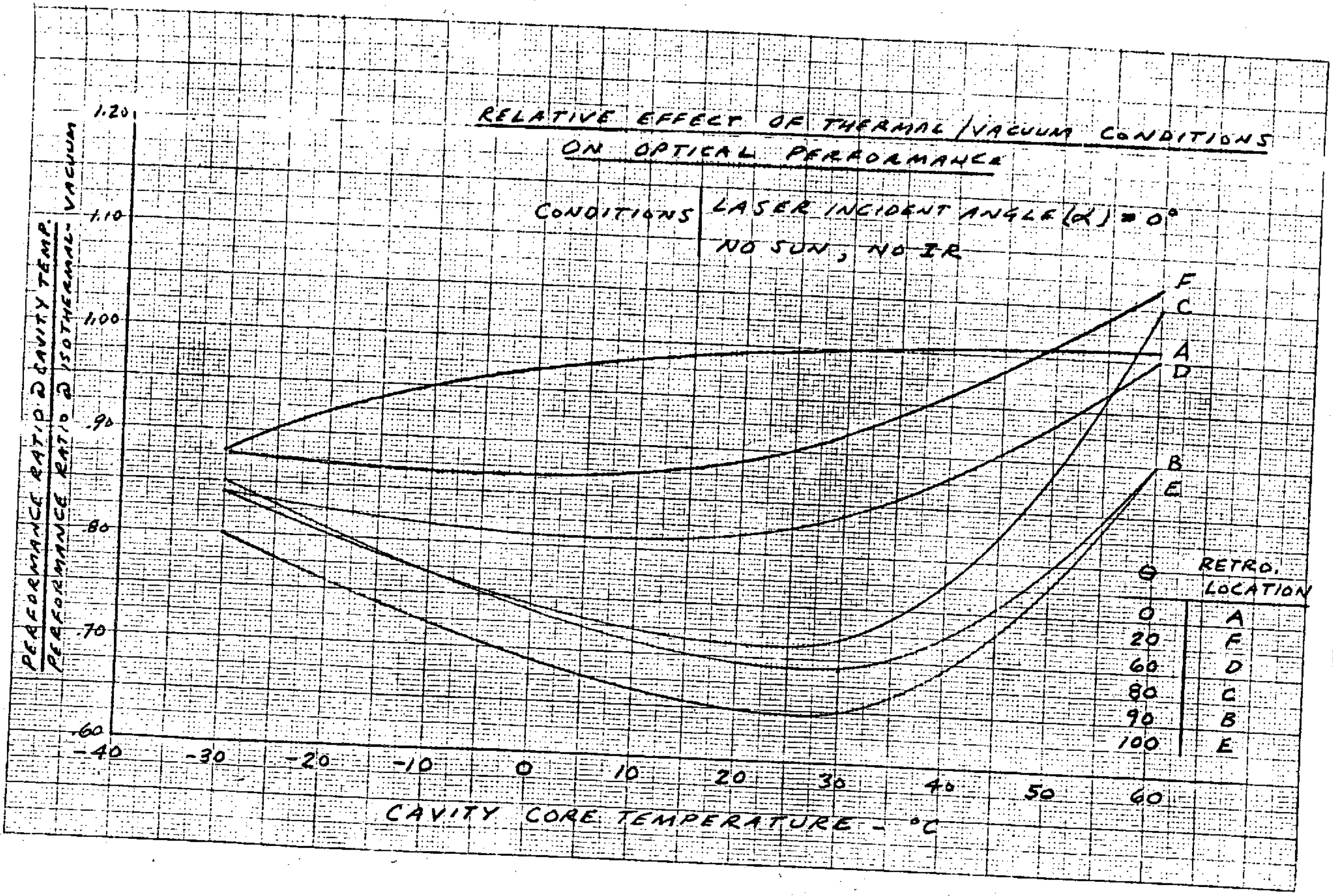
$\frac{\text{RATIO ANNULAR}}{\text{(RATIO FULL FIELD)}}$ = .050



α = +30°
EXPOSURE: 1/250 SEC

$\frac{\text{RATIO ANNULAR}}{\text{RATIO FULL FIELD)}}$ = .007

LASER INCIDENT ANGLE = α

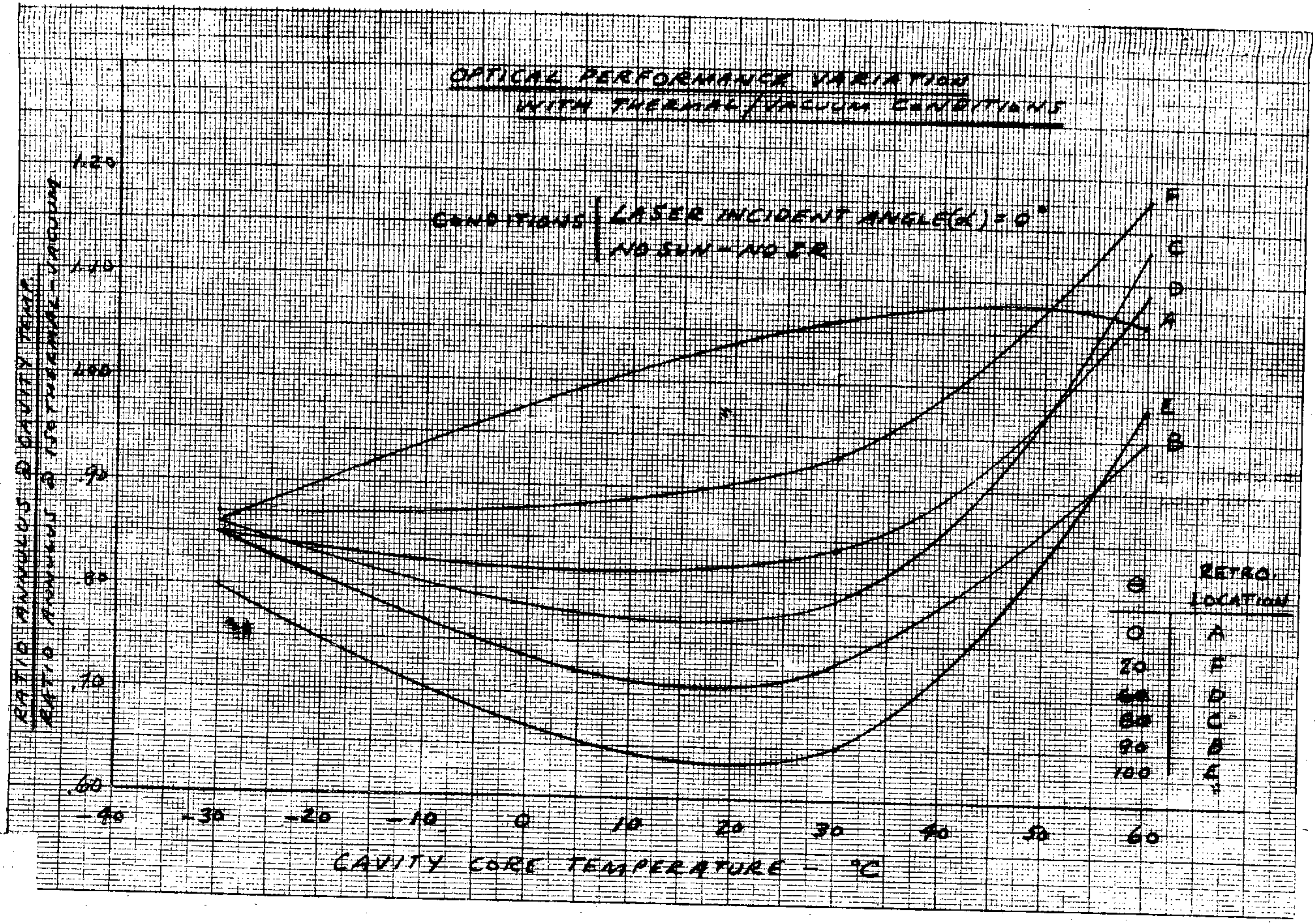

RELATIVE EFFECT OF THERMAL/VACUUM CONDITIONS ON OPTICAL PERFORMANCE
CONDITIONS | LASER INCIDENT ANGLE (α) = 0°
NO SUN, NO IR
PERFORMANCE RATIO @ CAVITY TEMP. / PERFORMANCE RATIO @ ISOTHERMAL-VACUUM
1.20
1.10
1.00
.90
.80
.70
.60
-40
-30
-20
-10
0
10
20
30
40
50
60
CAVITY CORE TEMPERATURE - °C
F
C
A
D
B
E
θ
RETRO. LOCATION
0 A
20 F
60 D
80 C
90 B
100 E

LAGEOS

RELATIVE EFFECT OF THERMAL/VACUUM CONDITIONS ON OPTICAL PERFORMANCE

PERFORMANCE RATIO @ CAVITY TEMPERATURE / PERFORMANCE RATIO @ ISOTHERMAL-VACUUM

T/V CONDITION		1 SUN - NO IR						NO SUN - 1 IR					
CAVITY CORE TEMPERATURE		-30C			+30C			-30C			+30C		
RETROREFLECTOR LOCATION		A	B	C	A	B	C	A	B	C	A	B	C
LASER INCIDENT ANGLE (α)-DEGREES	+30	1.33	X	X	1.00	X	X	1.0	X	X	1.33	X	X
	+15	1.02	1.34	X	1.07	1.16	X	.95	1.06	X	1.25	1.25	X
	0	1.02	1.21	1.02	1.09	.90	.94	.95	1.03	1.02	1.08	1.05	.96
	-15	1.15	X	X	1.24	X	X	.98	X	X	1.28	X	X
	-30	1.12	X	X	1.15	X	X	.92	X	X	1.23	X	X


OPTICAL PERFORMANCE VARIATION
WITH THERMAL/VACUUM CONDITIONS
CONDITIONS | LASER INCIDENT ANGLE(α) = 0°
NO SUN - NO ER
RATIO ANNULUS @ CAVITY TEMP
RATIO ANNULUS @ ISOTHERMAL-VACUUM
1.20
1.10
1.00
.90
.80
.70
.60
-40
-30
-20
-10
0
10
20
30
40
50
60
CAVITY CORE TEMPERATURE - °C
F
C
D
A
E
B
θ
RETRO. LOCATION
0 A
20 F
40 D
60 C
90 B
100 E

LAGEOS

COMPARISON-THERMAL/OPTICAL ANALYSIS AND TEST RESULTS

	THERMAL/OPTICAL ANALYSIS	THERMAL/OPTICAL TEST
RETROREFLECTOR	MATH MODEL	A (SERIAL NO. 3)
DIHEDRAL ANGLES (ARC SEC)	1.0, 1.5, 2.0	1.81, 1.08, 1.42
WAVE FRONT DEVIATION OF EACH SECTOR	.25λ	0.15λ, 0.15λ, 0.10λ 0.10λ, 0.10λ, 0.10λ
DIAMETER OF FFDP CENTROID (ARC SEC)	16.5	17.6
DATA ANNULUS DIAMETERS (ARC SEC)	13.2 - 16.9	13.2 - 16.9
ISOTHERMAL-VACUUM $\frac{\text{ANNULAR RETURN}}{\text{FULL FIELD RETURN}}$	.177 (α = 0) .086 (α = -15°	.124 α = 0 .084 α = -15°
THERMAL-VACUUM $\frac{\text{ANNULAR RETURN}}{\text{FULL FIELD RETURN}}$	.169 (α = 0) .081 (α = -15°)	.135 (α = 0) .102 (α = -15°)
ΔT AXIAL (°C)	1.9	*
ΔT RADIAL (°C)	1.3	*
CAVITY CORE TEMPERATURE	+30°C	+30°C (1 SUN-NO IR)

*DATA UNKNOWN

LAGEOS

VIBRATION EFFECTS ON OPTICAL PERFORMANCE

(ISOTHERMAL VACUUM)

RETROREFLECTOR LOCATION		D		F	
CONDITION		PRE-VIB.	POST-VIB.	PRE-VIB.	POST-VIB.
LASER INCIDENT ANGLE (∝) - DEGREES	+30	.023	.023	.002	.002
	+15	.039	.044	.036	.037
	0	.088	.089	.088	.082
	-15	.038	.036	.044	.044
	-30	.002	.002	.006	.007

LAGEOS

VIBRATION EFFECTS ON OPTICAL PERFORMANCE

(NO SUN-NO IR, -30°C)

RETROREFLECTOR LOCATION		D		F	
CONDITION		PRE-VIB.	POST-VIB.	PRE-VIB.	POST-VIB.
LASER INCIDENT ANGLE (∝) - DEGREES	+30	.020	.020	.002	.002
	+15	.033	.033	.033	.033
	0	.075	.082	.077	.083
	-15	.036	.032	.039	.036
	-30	.002	.002	.006	.006

LAGEOS

VIBRATION EFFECTS ON OPTICAL PERFORMANCE

(NO SUN-NO IR, +30°C)

RETROREFLECTOR LOCATION		D		F	
CONDITION		PRE-VIB.	POST-VIB.	PRE-VIB.	POST-VIB.
LASER INCIDENT ANGLE (∝) - DEGREES	+30	.021	.020	.002	.001
	+15	.035	.032	.035	.030
	0	.074	.067	.081	.070
	-15	.036	.030	.043	.036
	-30	.002	.002	.006	.004

LAGEOS

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS:

- BASED ON THE THERMAL/OPTICAL TEST RESULTS, THE LAGEOS DESIGN, AS REFLECTED IN THE LAGEOS TEST ARTICLE DESIGN, WILL MEET THE REQUIREMENT FOR LESS-THAN-50 PERCENT OPTICAL PERFORMANCE DEGRADATION, FROM ISOTHERMAL PERFORMANCE, UNDER ORBITAL WORST-CASE THERMAL CONDITIONS.

- NO SIGNIFICANT OPTICAL PERFORMANCE CHANGES RESULT FROM EXPOSURE OF THE LAGEOS RETROREFLECTOR/MOUNT DESIGN, AS REFLECTED IN THE LAGEOS TEST ARTICLE DESIGN, TO THE LAGEOS SATELLITE LAUNCH/BOOST VIBRATION ENVIRONMENT.

- RELATIVELY LARGE OPTICAL PERFORMANCE DIFFERENCES BETWEEN RETROREFLECTORS, FABRICATED TO THE PRESENT SPECIFICATION, ARE INDICATED BY THE TEST RESULTS.

RECOMMENDATIONS:

- MODIFY THE NASA-MSFC MOUNTING HARDWARE DRAWINGS TO REFLECT THE LAGEOS TEST ARTICLE MOUNTING HARDWARE DESIGN.

- CONSIDER RETROREFLECTOR SPECIFICATION CHANGES IF LAGEOS SYSTEM EVALUATION BY SAO INDICATES THAT MORE UNIFORM PERFORMANCE IS REQUIRED.

- CONSIDER ADDITIONAL THERMAL/OPTICAL ANALYSIS AND/OR TESTS TO SUPPORT DATA REQUIREMENTS FOR LAGEOS SYSTEM ANALYSIS.

Bendix
Aerospace
Systems Division

LAGEOS

DYNAMIC ENVIRONMENTS
&
VIBRATION TEST RESULTS

- ACOUSTICS
- SINUSOIDAL VIBRATION
- RANDOM VIBRATION

ACOUSTIC ENVIRONMENT

Frequency Range (Hz)	Pressure Level (DB)	Pressure (PSI)	Peak Acceleration (g's)
37.5 - 75	130	0.0090	0.24
75 - 150	135	0.0164	0.45
150 - 300	138	0.0231	0.64
300 - 600	140	0.0290	0.80
600 - 1200	141	0.0328	0.91
1200 - 2400	138	0.0231	0.64
2400 - 4800	134	0.0145	0.40
4800 - 9600	131	0.0103	0.29

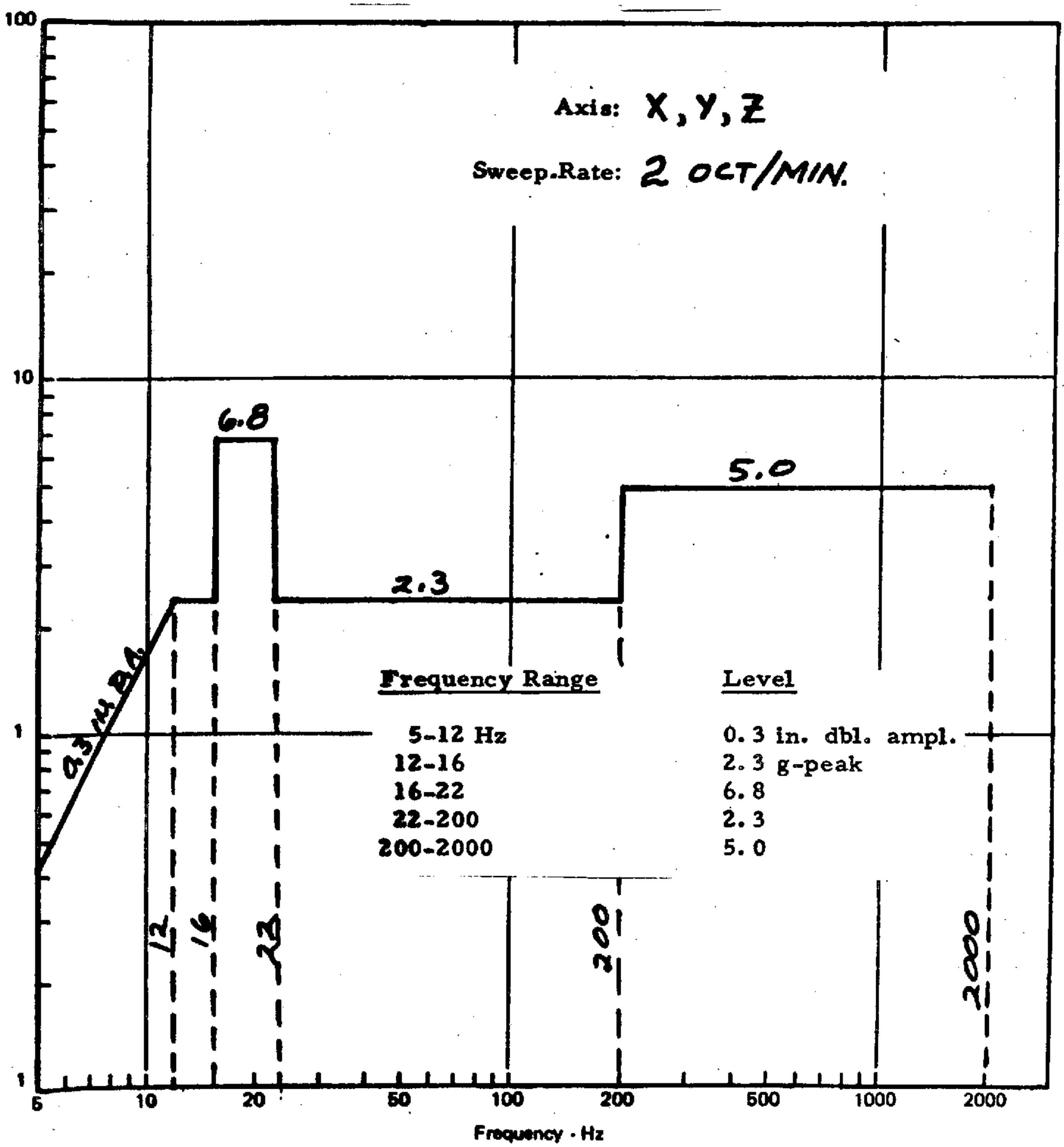
(re: 0.0002 dynes/cm^2 = 2.9×10^{-9} psi)

PURPOSE OF THE VIBRATION TESTS

- TO SUBJECT THE LAGEOS TEST ARTICLE TO THE LAGEOS SATELLITE QUALIFICATION-LEVEL VIBRATION ENVIRONMENT.
  - TO DETERMINE EFFECT, IF ANY, ON THERMAL/OPTICAL PERFORMANCE.
  - TO VERIFY DESIGN STRUCTURAL INTEGRITY.

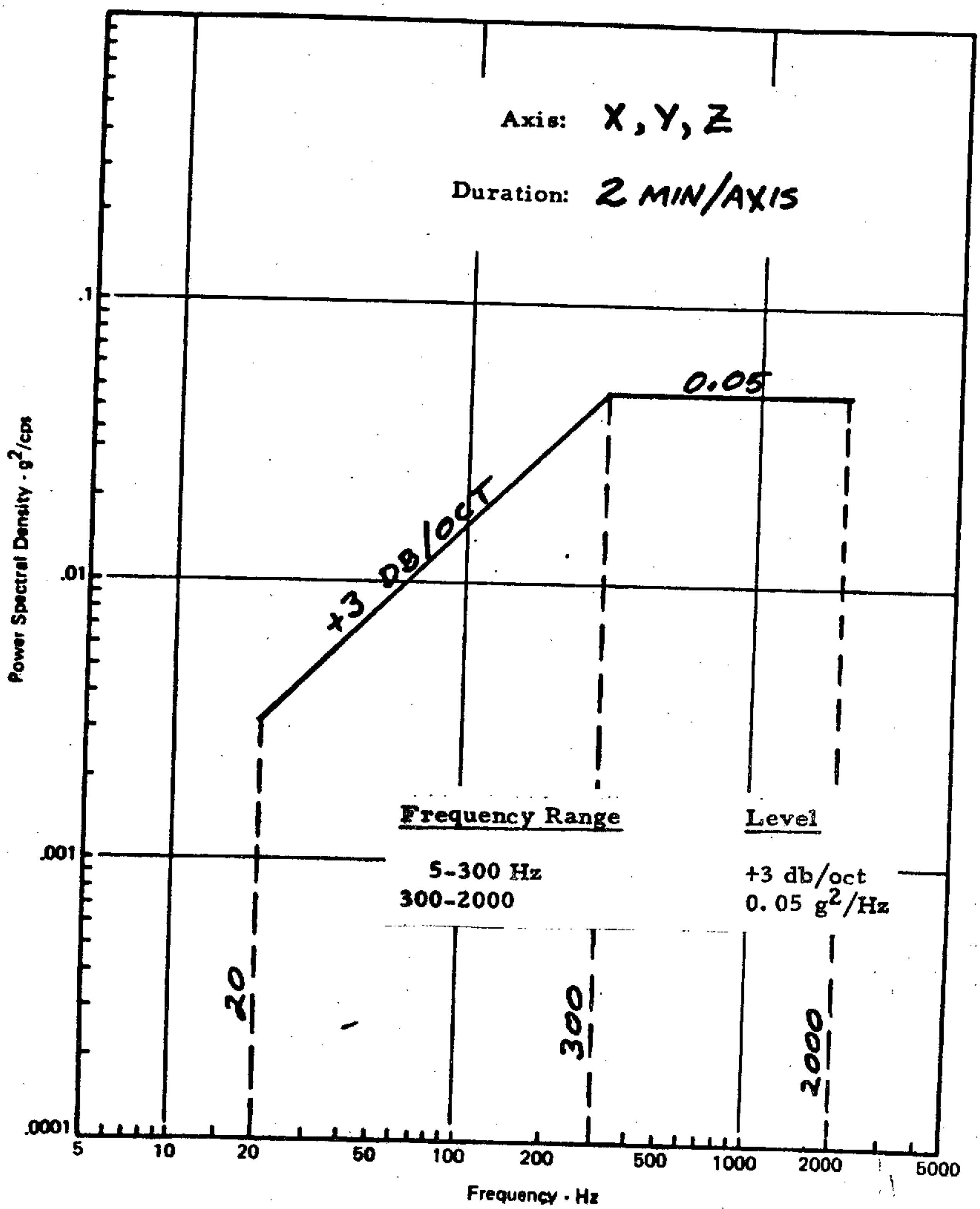
LAGEOS

SINUSOIDAL VIBRATION



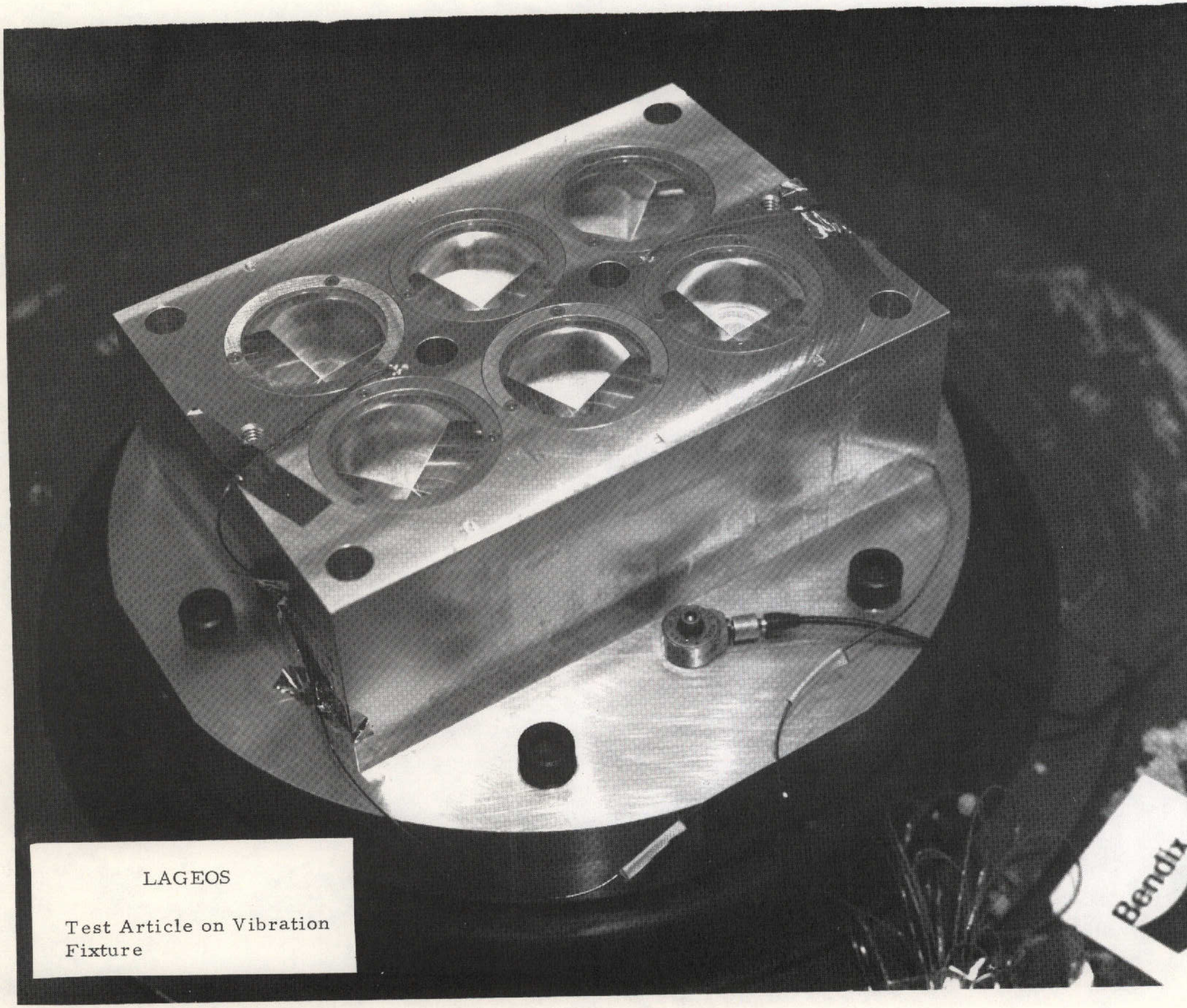
LAGEOS

RANDOM VIBRATION SPECTRUM



VIBRATION TEST SEQUENCE

1.	Z-AXIS	SINUSOIDAL
2.	Y-AXIS	SINUSOIDAL
3.	Y-AXIS	RANDOM
4.	Z-AXIS	RANDOM
5.	X-AXIS	SINUSOIDAL
6.	X-AXIS	RANDOM



LAGEOS

Test Article on Vibration Fixture

LAGEOS
Test Article Installed
on Vibration Shaker

TEST DISCREPANCIES

TDR No.	:	4009
DISCREPANCY	:	POSSIBLE FRACTURE ON "C" RETROREFLECTOR
RESOLUTION	:	MARK ON RETROREFLECTOR COULD NOT HAVE RESULTED FROM VIBRATION. INSPECTION, UNDER A MICROSCOPE, INDICATES MARK IS A CHIP, GENERATED DURING FABRICATION, WHICH HAD BEEN "STONED" TO PROHIBIT PROGRESSION. THE "STONED" TEXTURE OF THE SURFACE COULD NOT HAVE BEEN CAUSED BY CONTACT WITH THE KEL-F MOUNTING RING.

SCREW TORQUE VALUES

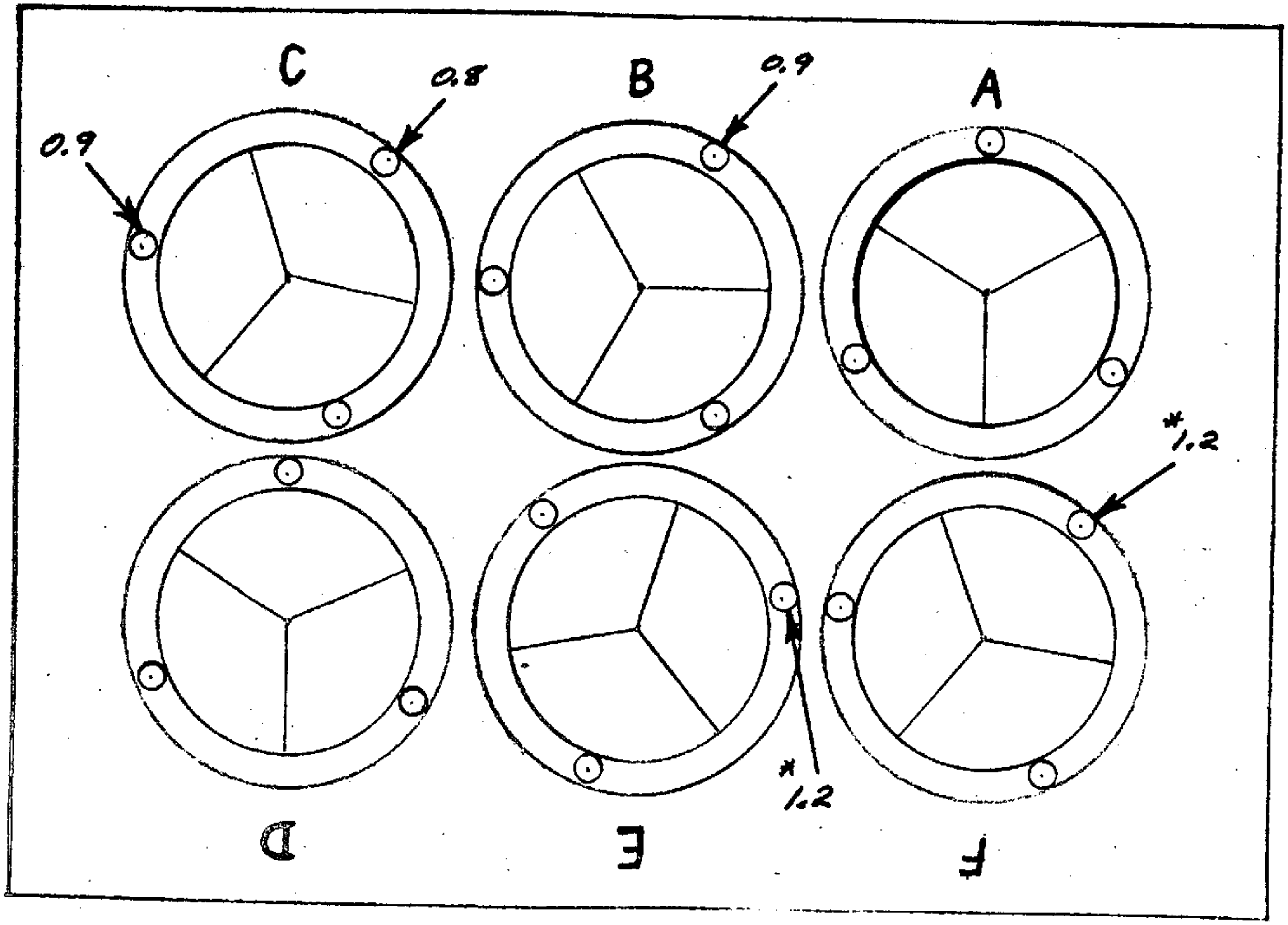
- PRIOR TO VIBRATION ALL SS SCREWS WERE REPLACED WITH ALUMINUM SCREWS.
- ALL 18 SS SCREWS RETAINED INITIAL TORQUE (2.2 $\pm$ 0.3 IN. LB.) THRU-OUT PRE-VIBRATION THERMAL-VACUUM TESTS.
- THE RETRO "C" ALUMINUM SCREWS RETAINED INITIAL TORQUE ($1.4 \begin{smallmatrix} +0.0 \\ -0.2 \end{smallmatrix}$ IN. LB.) THRU-OUT VIBRATION.
- AFTER POST-VIBRATION THERMAL-VACUUM TEST THREE ALUMINUM SCREWS WERE FOUND TO HAVE RETAINED LESS THAN THE INITIAL TORQUE VALUE:

RETRO "C"	0.8 IN. LB.
	0.9 IN. LB.
RETRO "B"	0.9 IN. LB.

POST-TEST TORQUE VERIFICATION

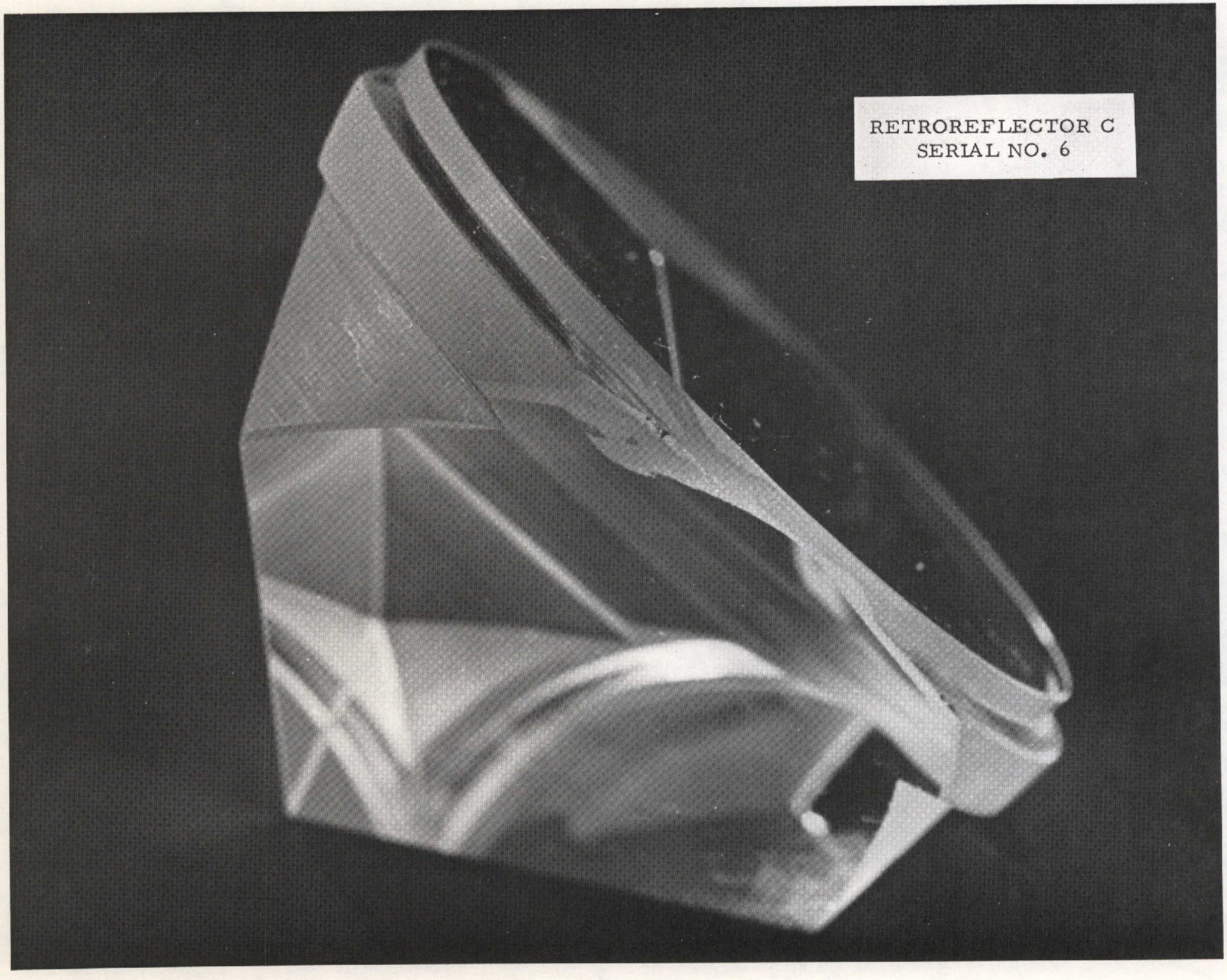
ORIGINAL TORQUE = 1.4 IN. LB. $^{+0.0}_{-0.2}$

CHANGES SHOWN BELOW; ALL OTHERS REMAINED AT 1.4 IN. LB.



CONCLUSIONS

- ACOUSTIC ENVIRONMENT IS NEGLIGIBLE.
- THE LAGEOS TEST ARTICLE ENDURED THE SPECIFIED VIBRATION ENVIRONMENT (I. E., LAUNCH LOADS) WITHOUT DAMAGE TO COMPONENTS, WITH NO OPTICAL DEGRADATION OF THE RETROS, AND WITH NO SIGNIFICANT LOOSENING OF RETAINING SCREWS.


RETROREFLECTOR C
SERIAL NO. 6


RETROREFLECTOR C
SERIAL NO. 6


RETROREFLECTOR C
SERIAL NO. 6

Internal
Memorandum

APPENDIX M

Bendix Aerospace Systems Division

Date 28 May 1974

Letter No. 74-LAGEOS-22

Ann Arbor, Michigan

To J. Brueger

From J. Maszatics

Subject LAGEOS Acoustic Environment

Ref: Internal Memorandum No. LAGEOS-18 "LAGEOS Program Review Minutes", 30 April 1974

Introduction

As a result of the LAGEOS Program Review,Bendix was assigned an action item (no. 4.16 of referenced memo) which states, "Provide rational for not including exposure to the LAGEOS acoustic environment in the vibration test." The following is intended to close-out this action item.

Summary

Since the LAGEOS design does not incorporate low mass-to-area ratio components, it will be insensitive to the specified acoustic environment. By comparison the specified vibration environment will be an order of magnitude more severe than acoustics.

Analysis

The peak acceleration (g's) over a given acoustic frequency bandwidth is,

$$G = \frac{p}{g\ (m/A)}$$

where "p" is the acoustic pressure (psi), "g" is the acceleration of gravity (386.4 in/sec^2), "m" is the CCR mass (lb sec^2/in), and "A" is the CCR top face area (in^2). The acoustic pressure is calculated from the referenced pressure (0.0002 dynes/cm^2 or 2.9 x 10^{-9} psi) using the relationship,

$$p = (2.9 \times 10^{-9})\ 10^{db/20}$$

where "db" is the specified acoustic level.

Table 1 lists the specified LAGEOS acoustic environment, the corresponding pressure levels, and the calculated peak acceleration for the hex CCR. The following parameter values were used with the above equation to calculate accelerations:

$$mg = 0.07 \text{ lb}$$

$$A = 1.94 \text{ in}^2$$

The sinusoidal environment from 37.5 to 100 Hz is 2.3 g-peak compared to a maximum of 0.45 g-peak due to acoustics. The random vibration from 20 - 2000 Hz provides 9.8 g-rms, while over the same frequency range acoustics generate only a maximum of 0.91 g-peak. Obviously sinusoidal and random vibration are the dominant loading conditions up to 2000 Hz.

At 2000 Hz acoustic excitation will generate 0.40 g-peak which corresponds to a displacement of only 0.00000098 in. At higher frequencies the displacement will be even less. Even if system resonances occur above 2000 Hz, it is of no concern since transmissibility levels could not possibly be high enough to result in excessive response values.

Conclusion

The acoustic environment is less than 1g across the entire frequency spectrum. The specified sinusoidal and random vibration levels are much more severe (6.8 g and 9.8 g-rms, respectively). Hence, acoustics are insignificant compared to vibration and may be deleted from the test plan.

J Maszatics

J. Maszatics

JM:b

cc: L. Lewis
E. Granholm
J. McNaughton

Table 1 - LAGEOS Acoustic Environment

Frequency Range (Hz)	Pressure Level (DB)	Pressure (PSI)	Peak Acceleration (g's)
37.5 - 75	130	0.0090	0.24
75 - 150	135	0.0164	0.45
150 - 300	138	0.0231	0.64
300 - 600	140	0.0290	0.80
600 - 1200	141	0.0328	0.91
1200 - 2400	138	0.0231	0.64
2400 - 4800	134	0.0145	0.40
4800 - 9600	131	0.0103	0.29

(re: 0.0002 dynes/cm^2 = 2.9×10^{-9} psi)

Internal Memorandum

APPENDIX N

Bendix Aerospace Systems Division

Date 3 June 1974 Letter No. LAGEOS 25 Ann Arbor, Michigan

To J. Brueger

From J. Maszatics

Subject LAGEOS Circular Face CCR Dynamic Environment

References: (1) "LR^3 Array For EASEP" ADL report to Bendix, 30 June 1969.

(2) "Structural Analysis of a Typical Single Retro-Reflector" ADL report to Bendix, 11 December 1970.

(3) "Vibration Tests of Single Retro-Reflector Assemblies", ADL report to Bendix, 31 December 1970.

(4) Internal Memorandum No. LAGEOS-18, "LAGEOS Program Review Minutes", 30 April 1974.

Introduction

As a result of the LAGEOS Program Review, Bendix was assigned an action item (No. 4.15 of ref. 4) which states: "Provide rationale from ALSEP analysis/test data, for confidence in the structural integrity of the circular-faced retroreflector and its ring mount in the LAGEOS application." The following is intended to close-out this action item.

Summary

Structural analysis and vibration testing of the ALSEP CCR indicates that the LAGEOS dynamic environment will not subject the circular face CCR's to excessive stress levels.

Discussion

The vibration tests conducted during the Apollo 11 LR^3 program are discussed in Reference 1. Sinusoidal and random vibration tests using a fused-silica CCR were conducted without damage nor optical degradation.

Sinusoidal sweep tests were conducted in three mutually perpendicular directions from 5 to 2500 Hz at 40 g-peak input level. Maximum sinusoidal input to the LAGEOS CCR mounting hardware is 6.8 g-peak.

Three axes random testing was performed at 16.1 g-rms input to the LR^3 array. Resulting response levels varied from 23 to 65 g-rms. LAGEOS random input to the CCR mount has been specified at 9.8 g-rms.

Assuming the LAGEOS mounting system does not appreciably amplify the dynamic levels to the CCR, it is valid to compare LAGEOS with LR^3. Such a comparison indicates that the LAGEOS CCR environment is less severe than the LR^3 test levels.

As a result of structural analysis, reference 2 states that the fused silica CCR with circular face and tabs is capable of withstanding a static load of 2900 g's without exceeding the material yield stress. Neither LR^3 test nor LAGEOS specification environments exceed this value.

Reference 3 presents the vibration test results for the Apollo 15 LR^3 program. A fused-silica CCR was subjected to sinusoidal dwell at 100 and 300 Hz without damage. At 100 Hz an input level of 170 g-peak was applied for three minutes per axis. Response levels from 400 to 600 g were recorded. At 300 Hz an input level of 90 g-peak was applied for 1.5 minutes per axis.

Conclusion

The ALSEP (Apollo 11 and 15) LR^3 vibration test levels were considerably more severe than the specified LAGEOS environments. In addition,structural analysis of a fused-silica, circular faced, three-tab CCR show it to be capable of sustaining load conditions which are much higher than those imposed by ALSEP environments.

Assuming that the LAGEOS CCR mounting system is dynamically similar to the LR^3 mounting system, it can be stated that CCRs will survive LAGEOS vibration tests without damage, since they have already demonstrated the ability to survive the more severe ALSEP environments.

Structural analysis of a fused-silica CCR, conducted during the LR^3 program, has shown a capability to withstand a static load of 2900 g. Hence, any CCR mounting mechanism that prevents impact with the cavity wall should be sufficient.

The present design utilizes a pair of KEL-F mounting rings which protect the CCR tabs from direct contact with the cavity wall. Hence, the LAGEOS dynamic environment should not damage nor impair the optical performance of the CCRs.

J Maszatics

J. Maszatics

cc: E. Granholm
L. Lewis
J. McNaughton

APPENDIX P

Optical Analysis Cases

Case No.	Retroreflector Dihedral Angle	Emerging Wavefront Deviation	Thermal Gradient	Laser Field Angles
2.1	90° 0' 1.5" (three places) ("perfect " config.)	0	0°C	0° -15°
2.2		$\lambda/4$	0°C	0° -15°
2.3.a		$\lambda/4$	two conditions	0°
2.3.b		$\lambda/4$	one condition	0° -15°
2.4.a	90° 0' 1.0" 90° 0' 1.5" 90° 0' 2.0" ("tolerance" config.)	$\lambda/4$	0°C	0° -15°
2.4.b.2		$\lambda/4$	one condition	0° -15°
2.5.a	90° 0' 1.5" (three places) ("perfect" config.)	$\lambda/4$	Unit Axial temp. gradient	0°
2.5.b		$\lambda/4$	Unit Radial temp. gradient	0°